A METHOD FOR THE ANALYSIS OF PILE SUPPORTED FOUNDATIONS CONSIDERING NONLINEAR SOIL BEHAVIOR

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PREFACE

This study presents a procedure which was developed for analysis of pile supported foundations.

In this study special emphasis is placed on pile supported bridge bents. Two bridge bents which were designed and constructed by the Texas Highway Department have been analyzed.

The computer program included in this report is a modification of a program developed at The University of Texas at Austin by Lymon C. Reese and Hudson Matlock. The program is written in FORTRAN IV. It was developed for the CDC 6600 system but it is also operational on the IBM 360 system.

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ABSTRACT

This report contains a review of existing methods of analysis of foundations supported on pile groups consisting of vertical and batter piles. The method of analysis developed at The University of Texas at Austin, referred to here as the UT method, is modified to take into account the interaction effect of axial and lateral loading and also to consider some special boundary conditions associated with bridge bents.

The study also compares the UT method with other methods of analysis available, bringing out its features and advantages. The assumptions and limitations involved in the UT method are indicated.

A generalized computer program has been written to aid in the solution of the problem. With the aid of this computer program it is possible to take into account the nonlinear behavior of the soil with respect to applied load. Documentation of the program is provided in the form of a list of the notation used, a listing of the program including subroutines, and forms necessary for input of data. Two example problems are solved using the computer program. A complete listing of input and output data for the example problems is provided.

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NOMENCLATURE

Symbol	Typical Units	Definition
a	in	Horizontal distance to pile top
A	-	Recursive coefficeint
b	in	Vertical distance to pile top
B	-	Recursive coefficient
c	lb/in^2	Cohesion
C	-	Recursive coefficient
E	lb/in^2	Modulus of elasticity (Pile)
E_s	lb/in^2	Soil modulus
F_h	lb	Horizontal load on pile
F_v	lb	Vertical load on pile
h	in	Increment length
I	in^4	Pile moment of inertia
J_x	lb/in	Axial secant modulus
J_y	lb/in	Lateral secant modulus
J_m	in-lb/in	Moment secant modulus
K_A	-	Coefficient of active earth pressure
K_o	-	Coefficient of passive earth pressure
M	in-lb	Moment
M_t	in-lb	Moment on pile top
p	lb/in^3	Soil reaction
P_V	lb	Vertical load on foundation

Symbol	Typical Units	Definition
P_H	lb	Horizontal load on foundation
R	lb-in^2	Pile stiffness (EI)
V	lb	Shear
w	in	Pile diameter or pile width
x_t	in	Axial movement of pile top
X	in	Distance from soil surface
y	in	Lateral pile deflection
α	rad	Rotation of foundation
γ	lb/in^3	Soil unit weight
ΔH	in	Horizontal foundation movement
ΔV	in	Vertical foundation movement
ϵ	in/in	Strain
θ	rad	Pile batter
σ	lb/in^2	Stress
σ_Δ	lb/in^2	Deviator stress $(\sigma_1 - \sigma_3)$
ϕ	degrees	Angle of internal friction

CHAPTER I

INTRODUCTION

The purpose of this study is to review and expand upon existing methods for analyzing foundations which are supported on pile groups consisting of vertical and batter piles. The expansions of the existing methods are aimed at solutions for problems of bridge bents supported on piling. It is believed that the resulting method will apply equally well to other types of piling supported foundations, if the cap connecting the piles is rigid in relation to the flexibility of the pile.

When a grouping of vertical piles is subjected to horizontal loading, the stiffness of the piles may result in a portion of the horizontal load being transferred to the lower soil strata. A larger portion of the horizontal load will be transferred directly to the upper soil layers as the piles bend laterally. If the upper soil layers are weak and highly compressible, the lateral deflection which occurs may be excessive.

By using batter piles in a pile grouping, the portion of the horizontal load transferred to the upper soil layers is reduced, since the component of the horizontal force parallel to the axis of the batter pile is transferred to the lower strata through axial loading. This transfer of horizontal load into axial load in batter piles will usually reduce the deflection of the pile group, since piles are stiffer under axial loading than under bending type loading and the lower soil strata are usually stiffer than the upper soil strata.

It is desirable to know the forces on each pile and the load deflection behavior of each pile in order to make a more complete appraisal of the adequacy of a pile-supported foundation. When only vertical piles are used and the only load applied is a vertical load through the centroid of the pile group, the vertical load is distributed equally to the individual piles and only the axial behavior of the piles need be considered. However, if horizontal loads are also applied and if batter piles are included in the pile group, then the problem becomes more complex.

A number of methods have been proposed for analyzing the general problem of vertical and horizontal loading on a pile group which consists of vertical and batter piles. All of these methods involve approximations and assumptions, but four methods have been selected which have a degree of rationality in their approach. Three of these four methods are outlined briefly and the limitations, assumptions and approximations involved in these three methods are noted and compared with the fourth method which was developed at The University of Texas at Austin, by Lymon C. Reese and Hudson Matlock[8,14,15]. The method developed by Reese and Matlock, referred to in this report as the UT method, was intended for use in analyzing off-shore drilling platforms which are supported on vertical and batter piles, but the method has been applied successfully to other types of pile supported structures. The UT method has several definite advantages over other methods. These advantages will be discussed.

In this report the UT method will be presented with certain modifications and additions as formulated by the author. The basic procedures involved are not changed from those developed by Reese and Matlock, but some alterations have been made for the solution of individual laterally loaded piles. A procedure is also presented for introducing the soil properties into a calculation of the lateral interaction of the pile with the soil. The modifications to the UT method were incorporated into a computer program and two example problems are solved by using the program.

CHAPTER II

METHODS OF ANALYSIS OF BATTER PILE FOUNDATIONS

GENERAL CONSIDERATION OF PROBLEM

A procedure is available for design of pile supported foundations in which all the piles are vertical and in which the applied loads may be resolved into a vertical force through the centroid of the pile group. The procedure involves two steps. First, the allowable bearing capacities of the individual piles are obtained by applying an appropriate safety factor to the ultimate capacities of the piles as determined either from load tests, from driving characteristics, or from other theoretical procedures. Second, the total applied load is divided by the number of piles in the foundation to obtain the load on each pile. If this load does not exceed the allowable bearing capacities of the individual piles, then the design is considered adequate. Terzaghi and Peck[24] also recommended that the design be checked by computing the allowable bearing capacity of the pile group against breaking into the ground as a unit.

The above procedure for vertical piles and vertical loads gives no indication of the deflections which occur for intermediate loads, but only the allowable load which may be sustained with a safety factor against excessive settlement of the foundation. The procedure must also be considered as an approximation since it is felt that all piles do not carry the same load. The load which is carried by a pile is influenced by the spacing of adjacent piles but the exact relationship of this influence is not known. This influence is frequently estimated by empirical rules of thumb or approximations.

If the pile group includes batter as well as vertical piles and if the group is subjected to horizontal and vertical loading, the analysis becomes more complicated. In a rigorous analysis the horizontal and moment resistance offered by the piles must be considered, as well as the axial resistance. Robertson[19] discusses some of the assumptions and approximations frequently employed to handle horizontal and moment resistance. Robertson points out that some of these assumptions may misrepresent a batter pile structure and that the methods of analysis which employ these assumptions may have limited usefulness due to the inaccuracy of the approximations involved.

There is some degree of approximation in all methods which have been proposed for the analysis of foundations supported by batter piles. Brief discussions of the methods proposed by Carl Culmann, as reported by Terzaghi and Peck[24], C. P. Vetter[25] and Alexander Hrennikoff[7] will be presented in the following sections. The discussions will include lists of the limitations and approximations involved in each method. These methods are considered to be representative of the available methods for analysis of foundations supported on batter piles.

Culmann's Method

According to Terzaghi and Peck[24], the method proposed by Carl Culmann is based on the resolution of the applied force into three components. These components act in directions parallel to the axes and through the centroid of three pile groups which support the foundation. A pile group is defined as all piles driven in a particular direction, and Culmann's method requires that the foundation be supported by three pile groups. The basic procedure is shown graphically in Fig. 1. Definitions are as follows:

R = Force applied to foundation

P_1, P_2, P_3 = Component of force R acting on and parallel to pile groups 1, 2 and 3 respectively.

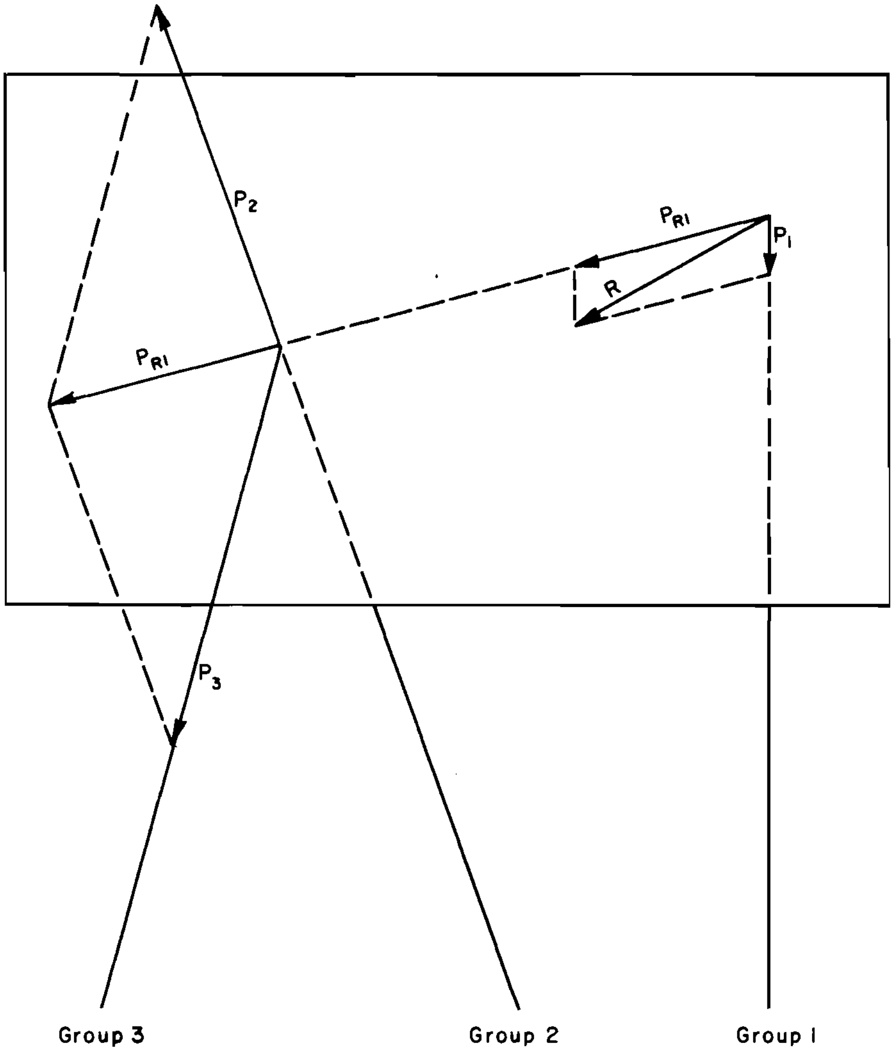


Fig. 1. Graphical representation of Culmann's method.

The method is subject to the following limitations:

1. Solution is limited to two dimensional configurations.
2. The foundation must be supported by three nonparallel groups of piles.
3. No load-displacement relationships are considered for the foundation or the piles.

The assumptions and approximations involved are as follows:

1. The piles develop only axial forces.
2. The foundation is statically determinate.

Vetter's Method

The method presented by C. P. Vetter[25] is similar to the methods developed earlier by Swedish engineers. Vetter mentions a number of earlier works in the acknowledgments to his paper.

This method utilizes the concept of an elastic center (center of rotation) about which the foundation rotates. Forces through the elastic center cause only translation, without rotation, while a moment about the elastic center will cause a rotation, without translation. This translation and rotation of the foundation will cause movement of the pile heads. The method proposed by Vetter consists of locating the elastic center of the foundation, and determining the forces required to produce small elastic deformations in the piles. The applied loads are resolved into a force through the elastic center, and a moment about the elastic center. By adjusting the applied forces in relation to the forces required to produce elastic deformations in the piles, the forces on the piles due to the applied load may be found.

Axial, lateral, and rotational resistances of the piles are considered. The forces developed will correspond to an axial deflection, a lateral deflection and a rotation of the pile head. The lateral pile resistance offered by the pile is simulated by assuming the pile fixed at some depth "h" as shown in Fig. 2. The pile may be considered as pinned or fixed to the structure, depending on the rotational resistance offered by the pile.

The effect of lateral and rotational resistance is simulated by introducing imaginary "dummy" piles perpendicular to the real piles and considering the real piles as columns, pinned to the footing and pinned at some depth in the soil. The "dummy" piles are also considered as pinned columns.

By introducing "dummy" piles the lateral load-deformation characteristics are simulated by the axial behavior of the "dummy" piles. The location and length of the "dummy" piles will depend on the manner in which the pile is connected to the structure and the location of the point of fixity. The cross-sectional area of the "dummy" pile is expressed in terms of the cross-sectional area and stiffness of the real pile. If the pile shown in Fig. 2 is considered fixed to the structure, the "dummy" pile representation is shown in Fig. 3.

With the representation shown in Fig. 3, the resistance of the pile is simulated by axial forces in the pin-connected columns. The magnitude of the axial forces in the columns are determined by the force and moment through and about the elastic center, and by the location of the pile head. From the force in the pinned column representing the axial behavior of the real pile, the axial pile movement may be predicted. However, no method is available for predicting the lateral pile movement or the foundation movement.

Vetter's method is subject to the following limitations:

1. Solution is limited to two-dimensional configurations.

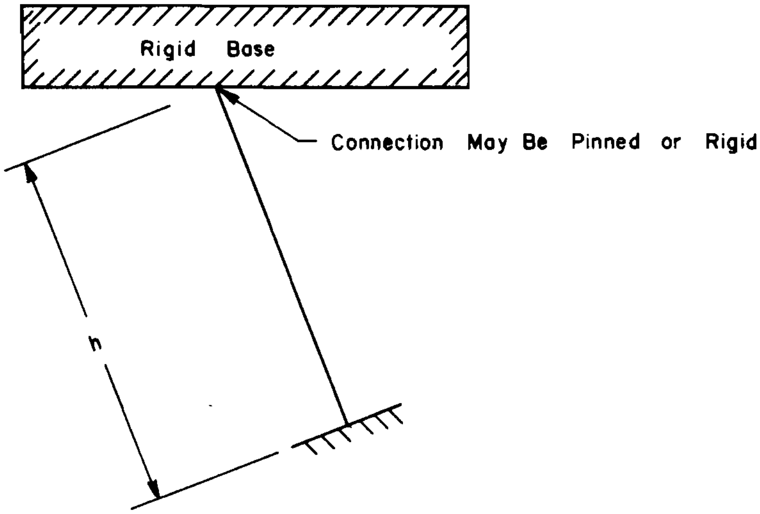


Fig. 2. Pile simulation for Vetter's method.

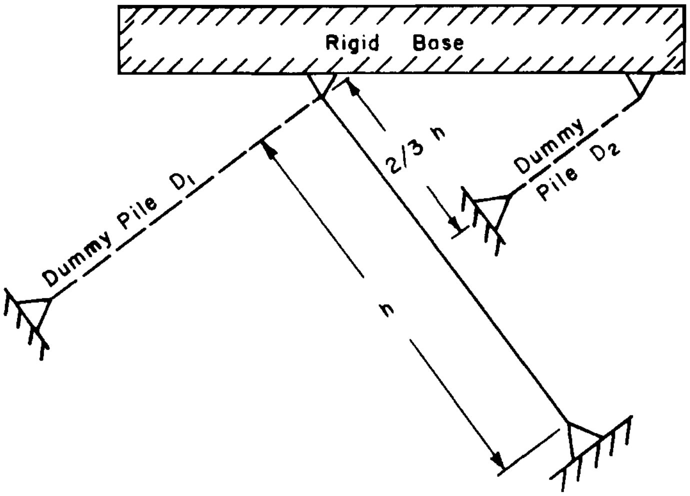


Fig. 3. Dummy pile representation for Vetter's method.

2. No method is suggested for determining the point of fixity.
3. Load-deformation behavior is limited to axial characteristics of pinned columns.
4. No prediction of foundation movement is possible.

The assumptions and approximations involved are as follows:

1. The foundation is rigid so that the pile tops maintain the same relative positions.
2. Pile deformations are elastically proportional to the applied loads.
3. The pile which is loaded laterally along its entire length may be simulated by a cantilever system.
4. The behavior of a real pile may be simulated by pin-connected columns.

Hrennikoff's Method

The method presented by Alexander Hrennikoff[7] in 1950 contained several important advances in technique. Probably the most important was the concept of a relationship between pile resistance and pile movements. Important relationships between movements and footing geometry were also developed.

The procedure consists of obtaining expressions for the forces and moments exerted on the structure by the piles resulting from a unit horizontal translation, a unit vertical translation, and a unit rotation of the structure. These forces and moments are summed in three equations of equilibrium, which are solved simultaneously for the movements of the foundation. Movements of the structure are related to the movement of the pile heads through the geometry of the structure. The movements of the pile heads are related to the forces on the pile heads through a set of pile constants. If these constants are known and the pile-head movements are known the pile forces and moments may be found.

Hrennikoff defines the pile constants as the forces with which the pile acts on the foundation when the pile head is given a unit displacement. There are three sets of constants, corresponding to three different kinds of displacements. The five pile constants (n, t_δ, m_δ, t_α, m_α) are shown in Fig. 4 with the corresponding displacements (δ_ℓ, δ_t, α).

By the Betti theorem[5] $t_\alpha = m_\delta$ leaving only four pile constants. The pile constant n is evaluated using an approximate formula. The constants t_δ, m_δ, and m_α are evaluated by considering the pile as a beam on an elastic foundation of infinite length, loaded at the free end. The elastic modulus of the soil is evaluated using approximate formulas developed by the author.

The pile constants, number of piles, and the geometry of the foundation are combined to evaluate the foundation constants. The foundation constants are defined as the resultant forces with which all piles act on the footing, when the footing is given a unit translation in the positive direction of one of the axes, or a unit rotation about the origin in a clockwise direction. The coordinate system and the foundation constants are shown in Fig. 5. The constants X_x, Y_x, M_x, X_y, Y_y, M_y, X_α, Y_α and M_α are obtained by giving the foundation a displacement $x = 1$, $y = 1$ or $\alpha = 1$ as mentioned previously.

By the Betti theorem $Y_x = X_y$, $M_x = X_\alpha$, and $M_y = Y_\alpha$ leaving only six constants to be evaluated. The equations of equilibrium for the footing are then

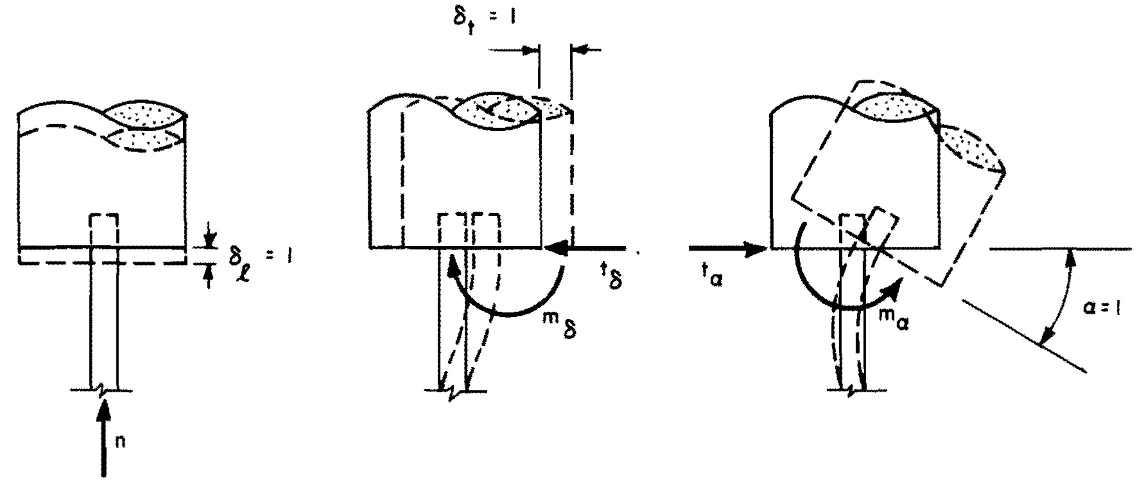


Fig. 4. Pile constants for Hrennikoff's method.

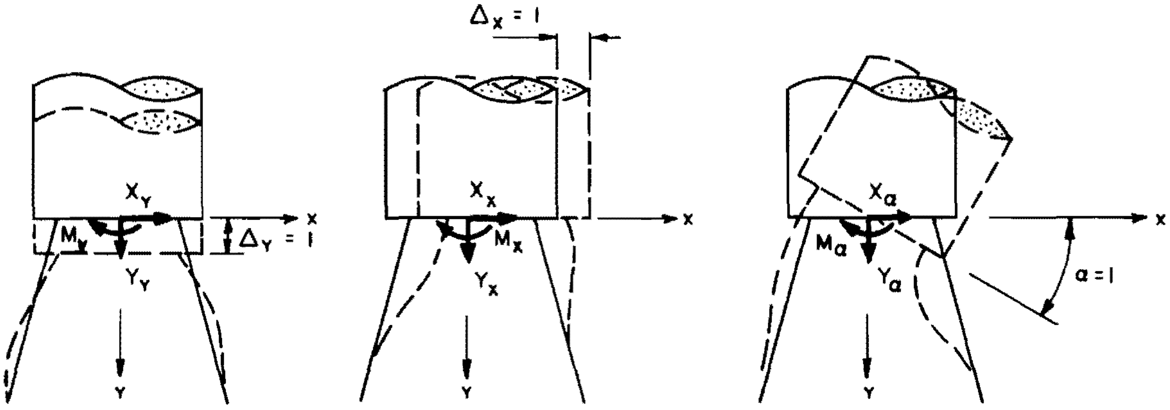


Fig. 5. Foundation constants for Hrennikoff's method.

$$X_x \Delta_x + X_y \Delta_y + X_\alpha \alpha + X = 0$$

$$X_y \Delta_x + Y_y \Delta_y + Y_\alpha \alpha + Y = 0$$

$$X_\alpha \Delta_x + Y_\alpha \Delta_y + M_\alpha \alpha + M = 0$$

where X, Y, and M are the forces and moment applied to the footing through and about the origin of the coordinate system. Once the structure movements (Δ_x, Δ_y and α) are found the forces and moments exerted by the piles may be found by working backwards. The movements of the pile head may also be found.

Hrennikoff's method is subject to the following limitations:

1. Solution is limited to two-dimensional configurations.
2. All piles must behave alike with regard to the load-deformation relation.

The approximations and assumptions involved are as follows:

1. Pile deformations are elastically proportional to the applied loads.
2. The foundation is rigid so that the pile tops maintain the same relative positions.
3. Foundation movements are small.
4. The piles are infinite in length.

COMPARISON OF METHODS WITH UT METHOD

Before beginning a detailed presentation of the UT method the basic assumptions involved in the method will be presented and compared with assumptions in the three methods previously discussed. It is felt that the advantages of the UT method will be apparent after this discussion.

Two Dimensional Configuration

The methods of Vetter, Culmann, and Hrennikoff are limited to the analysis of two dimensional problems. This does not limit the solution to foundations with piles in only one plane. It does, however, limit the solution to problems which have all piles parallel with, and symmetrical with respect to a vertical plane of symmetry. Similarly the resultant of all external forces and moments must be located in the plane of symmetry.

The UT method is also subject to the limitation of two dimensional analysis. There are structures for which a three dimensional solution is desirable. However, for many practical engineering problems a two dimensional analysis is sufficient. Three dimensional solutions[1,21] are available but will not be considered in this study.

Rigidity of the Foundation

Culmann's method, since it considers only equilibrium of the foundation, requires no assumptions concerning the rigidity of the foundation. For Vetter's and Hrennikoff's methods, as well as the UT method, the pile cap is assumed to be rigid so that the pile heads maintain the same relative positions before and after movement.

Connection of Piles to the Foundation

No consideration is given to the method of connecting the piles to the foundation in Culmann's method since the analysis is based on each pile group exerting a resultant force parallel to the piles in that group. For the methods of Vetter and Hrennikoff the piles may be fixed or pinned to the structure. For the UT method the piles may be fixed, pinned or attached in such a manner that the foundation exerts some constant rotational restraint on the pile. That is, the moment on the top of the pile divided by the slope at the top of the pile will be a constant.

Pile-Soil Interaction

For Culmann's method no pile-soil interaction is considered. Vetter's method simulates the axial interaction by considering the pile as a column. The lateral interaction is simulated by considering the pile as a beam with a fixed end.

The axial interaction, for Hrennikoff's method, is characterized by a constant. This constant is obtained by considering the axial compression for the pile as if it were a free standing column. The lateral interaction is characterized by a set of three constants obtained by considering the pile as a beam of infinite length on an elastic foundation.

For the UT method the axial pile-soil interaction is obtained from a load-deformation curve. No specific pile-soil interaction is specified, but the overall axial behavior is specified by the load-deformation curve. The lateral interaction is specified by a set of deflection-reaction curves. These curves, referred to as p-y curves, establish the relationship between the deflection of the pile and the reaction exerted by the soil. These curves are nonlinear as opposed to the linear behavior for the methods of Vetter and Hrennikoff. The procedure for obtaining p-y curves and the manner in which they are used in the analysis will be discussed later, but the point to be emphasized here is that in the UT method the soil-pile interaction is nonlinear as compared to the linear behavior which is assumed for the other methods of analysis.

Soils do not deflect linearly under load. This can be seen by noting the nonlinear shape of the stress-strain curves for soils as obtained from triaxial test. This would indicate that a consideration of a nonlinear interaction will yield more realistic results.

Load - Movement Relationships

Since Culmann's approach is based only on equations of equilibrium, no prediction of the movements resulting from the applied loads is possible. Similarly, Vetter's method provides no means for predicting foundation movement.

With Hrennikoff's method the foundation movement is defined by a horizontal and vertical translation and a rotation. These movements are related to the forces on the foundation by a set of foundation constants. The relationship between applied load and foundation movement is linear since they are related through a set of constants. Similarly the force-deflection relationship between pile-head movement and applied force is linear since they are related by the pile constants.

For the UT method the movement of the foundation is defined by two translations in the direction of the established coordinate system, and a rotation about the origin of the coordinate system. The loads on the foundation are resolved into two forces through the origin of the coordinate system and a moment about the origin. The movements of the pile heads are related to the foundation movement by the geometry of the system. The forces on the pile heads are related to the pile-head movements by nonlinear factors. All of these relations are combined into three equations of equilibrium for the foundation. From these equations the three movements of the structure are obtained. Since the relationships between pile-head deflection and pile reaction are nonlinear, an iterative process is necessary for establishing an equilibrium position for the structure. Once the equilibrium position is found, the deflection of the pile head and reactions may be obtained.

CONCLUSIONS

The UT method and Hrennikoff's method offer several major advantages over the methods of Culmann and Vetter. The method of Culmann was the first method proposed and it is limited by its failure to consider deflection of the foundation system. Vetter's method was the next method proposed and it introduces several improvements, but it is still limited by several assumptions.

The method of Hrennikoff and the UT method are similar in their approach. However, the UT method introduces two major improvements. Probably the most important of these is the use of nonlinear pile-soil resistance relationships. The second major improvement of the UT method is that it permits the rotational stiffness of the structure or pile-head restraint to be included in the analysis.

CHAPTER III

THEORETICAL DEVELOPMENT

PURPOSE

In the following sections the theory involved for the UT method will be developed. In the first section the coordinate systems and sign conventions for movements and forces will be established. In the second section the relationships between foundation movement and pile-head movements will be developed. Relations between foundation forces and pile reactions are established in section three. In the fourth section relations between pile-head movement and pile reaction will be developed. In the final section the equilibrium equations will be established.

COORDINATE SYSTEMS AND SIGN CONVENTIONS

Two types of coordinate systems are established. Examples are illustrated in Fig. 6. A horizontal axis "a" and a vertical axis "b" are established relative to the foundation. Foundation movements, forces and dimensions are related to these axes. The location of this system is completely arbitrary, but proper location will simplify calculations for most foundations.

For each pile an x-y coordinate system is established. The "x" axis is parallel to the pile and the "y" axis is perpendicular to the pile. Subscripts are used to indicate the particular pile. Pile deflection and forces are related to these systems.

The coordinates of the pile heads as related to the a-b axes are shown in Fig. 6. In the example all coordinates are positive. The batter of

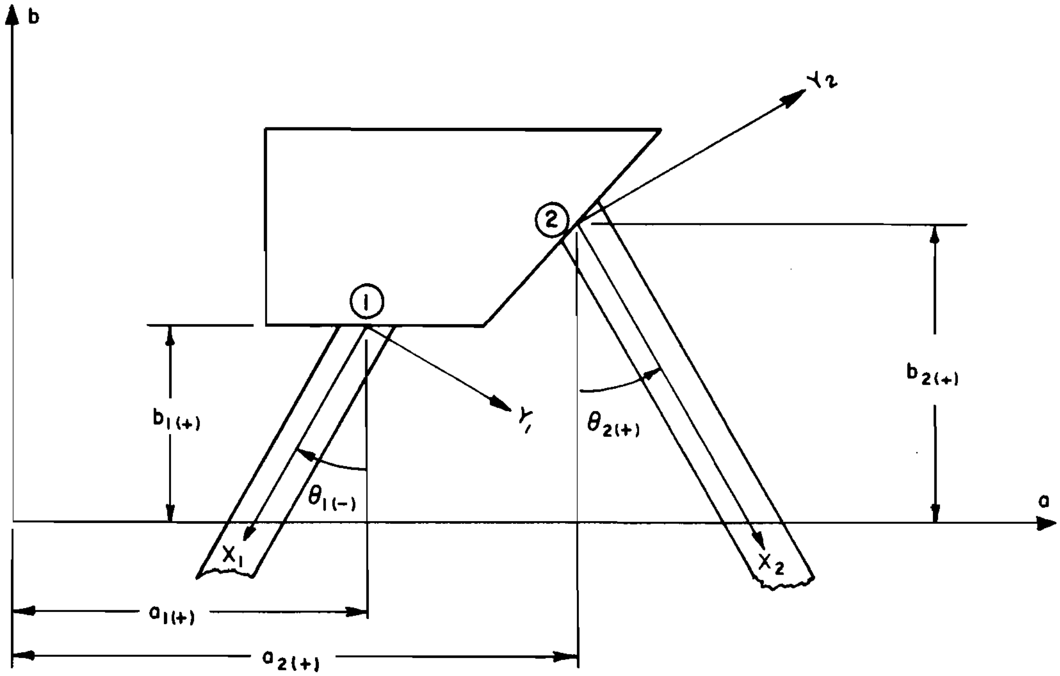


Fig. 6. Geometry of foundation.

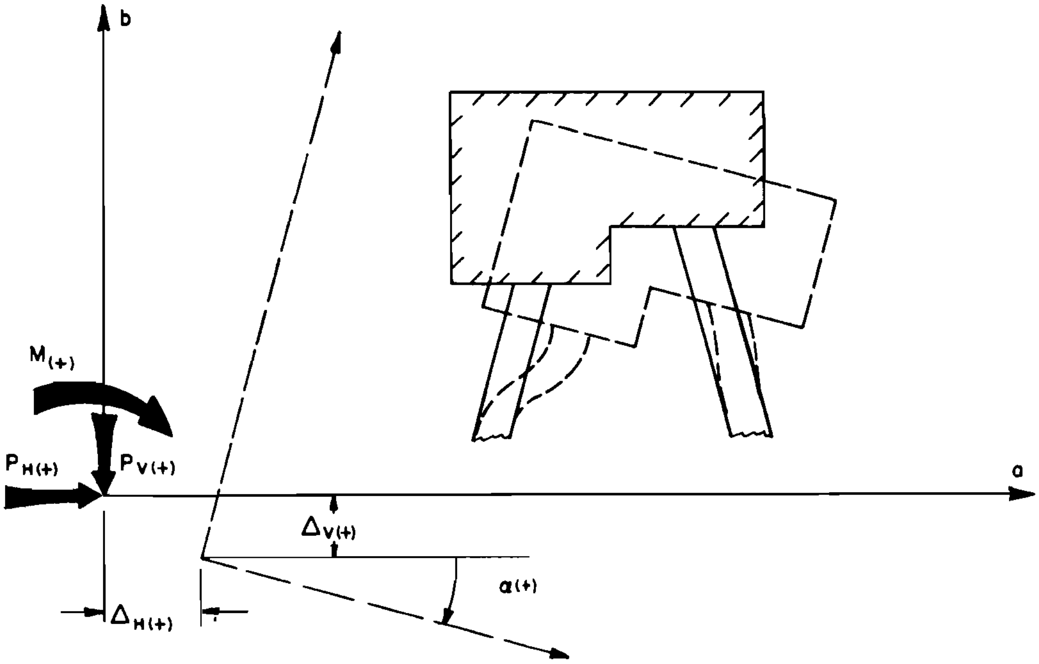


Fig. 7. Sign convention for foundation forces and movements.

the piles is positive counter clockwise from the vertical and negative clockwise from the vertical as shown.

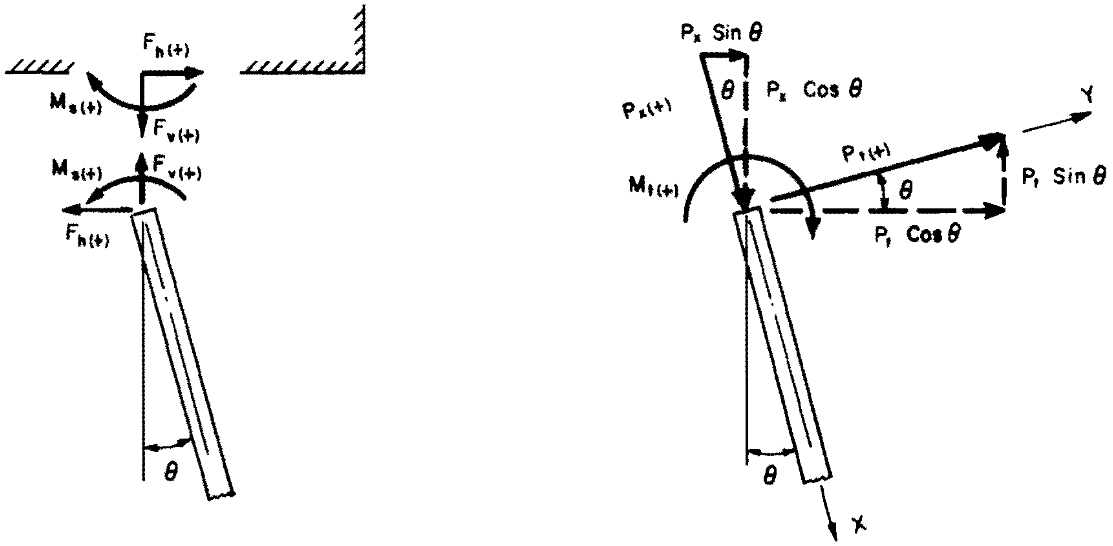
The external loads on the foundation are resolved into a vertical and horizontal component through the origin of the structural coordinate system and a moment about the origin. The sign convention established is illustrated in Fig. 7.

The external loads M, P_V, and P_H will cause the foundation to move. If the a-b coordinate system is considered to be rigidly attached to the foundation, the movement of the foundation may be related to the movement of the coordinate system. These movements (ΔV, ΔH, and α) are shown in Fig. 7 with positive signs.

Due to the movement of the foundation, forces will be exerted on the foundation by the piles. The sign convention for these forces is illustrated in Fig. 8.

The sign conventions illustrated by Fig. 8a are consistent with those previously established for the structure. The conventions illustrated by Fig. 8b are consistent with those established in the solution of laterally loaded piles[8]. The differences should be carefully noted. The inconsistencies are taken care of when the relations between foundation forces and pile forces are developed.

The sign conventions for movements of the pile head are consistent with the x-y coordinate system. A movement in the positive "x" direction, which constitutes an axial compression, is considered as a positive movement. A movement in the positive "y" direction is considered as a positive movement. A rotation of the pile head will cause a change in the slope at the top of the pile. The sign convention for slope is consistent with the usual



a. Forces and moment structure sign convention.

b. Forces and moment pile sign convention.

Fig. 8. Forces and moment on pile head.

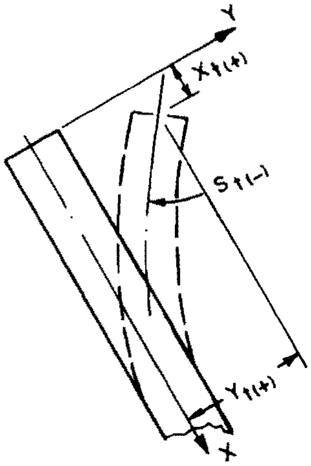


Fig. 9. Pile head movements x-y coordinate system.

manner in which slope is defined. The movements of the pile head are illustrated in Fig. 9.

RELATIONS BETWEEN FOUNDATION MOVEMENTS AND PILE-HEAD MOVEMENTS

When the structure moves the pile heads move. Two assumptions are made in order to relate structure movement to pile-head movement. The first assumption is that the foundation is rigid so that the pile heads maintain the same relative positions before and after movement. The second assumption is that the foundation movements are small. Because of this assumption the approximation

$$\alpha \approx \tan \alpha \tag{1}$$

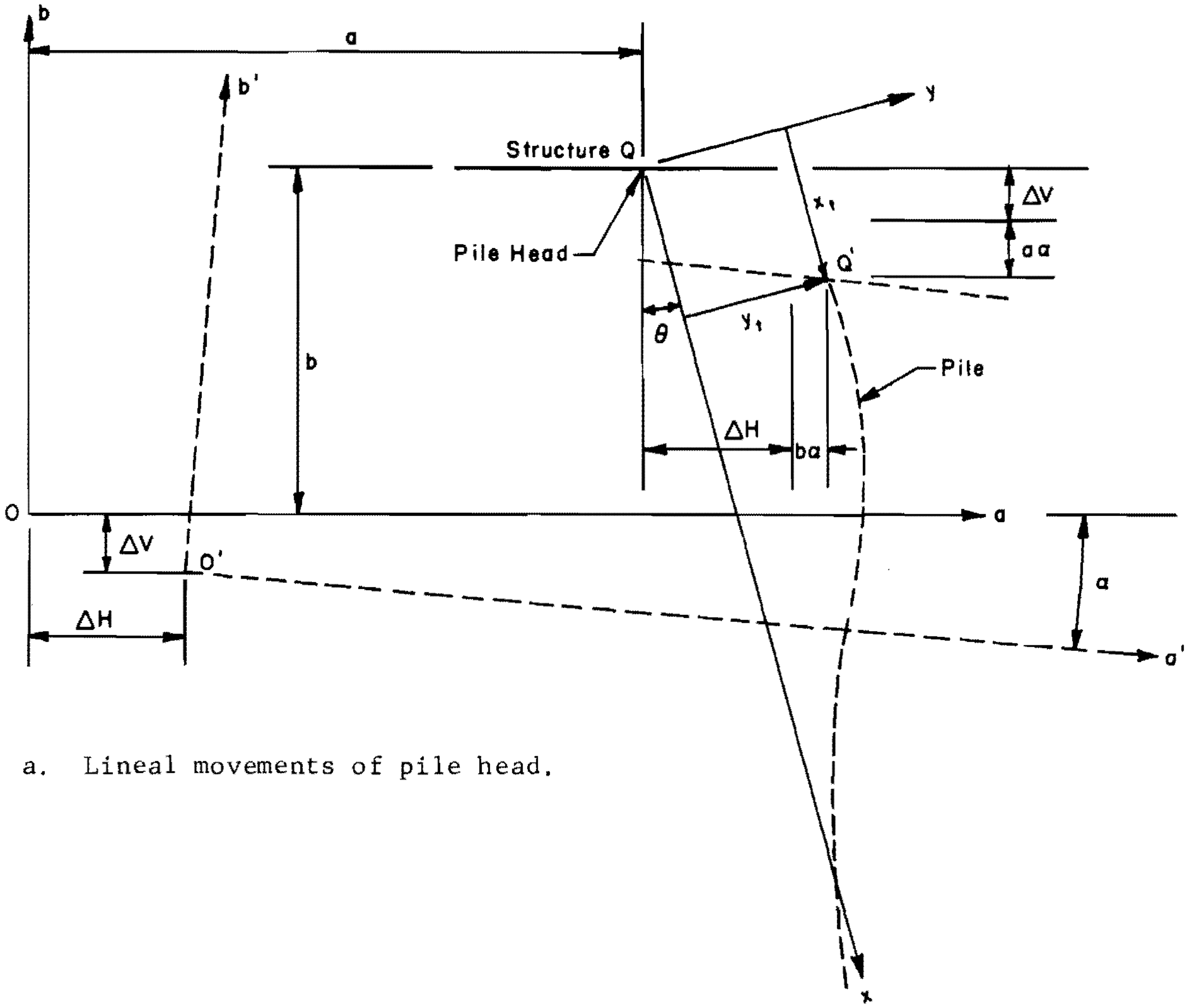
is valid.

In Fig. 10a diagrams are given of the lineal movements at the pile head of a given pile in terms of the structural movements. The movement of the structure is defined by the shift of the a-b axes to the position indicated by the a'-b' axes. The pile head movement is from point Q to point Q'. The total movement of the pile head is resolved into a component parallel to the "a" axis $(\Delta H + b\alpha)$ and a component parallel to the "b" axis $(\Delta V + a\alpha)$.

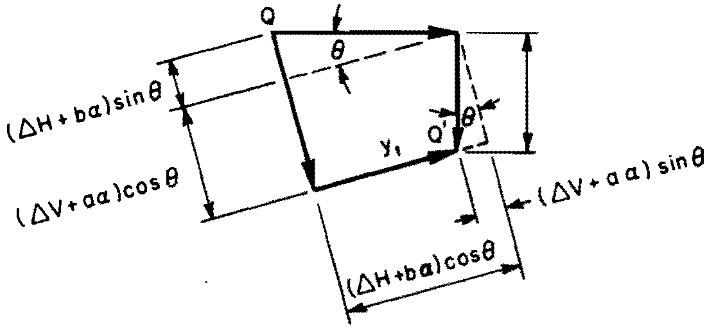
Figure 10b illustrates the resolution of the horizontal and vertical components of movement into components parallel and perpendicular to the direction of the pile. These movements are designated as x_t and y_t. Considering Fig. 10b the axial component of pile head movement may be written as

$$x_t = (\Delta H + b\alpha) \sin \theta + (\Delta V + a\alpha) \cos \theta \tag{2}$$

and the corresponding lateral movement as



a. Lineal movements of pile head.



b. Resolution of movement into components.

Fig. 10. Movements of pile head - structural coordinate system.

$$y_t = (\Delta H + b\alpha) \cos \theta - (\Delta V + a\alpha) \sin \theta \quad . \tag{3}$$

In addition to the lineal displacements of the pile head, the change in slope of a tangent to the elastic curve will be considered. The change in the slope will depend on the manner in which the pile is attached to the foundation. If the pile is fixed to the structure, then the change in slope will be equal to the rotation of the foundation. For the restrained case the change in slope will depend on the moment applied to the pile top. For a pinned connection the slope will depend on the deflected shape of the pile.

RELATIONS BETWEEN FOUNDATION FORCES AND PILE REACTIONS

The forces acting on the foundation and pile are illustrated, along with sign convention, in Fig. 8. It has been noted that inconsistencies in the sign conventions are present. These will be taken care of in the relations between the forces.

Considering Fig. 8 the relationship between moments on the structure and moment on the pile may be written as

$$M_s = -M_t \quad . \tag{4}$$

The relations between forces are obtained by resolving the forces on the pile into components in the horizontal and vertical directions. With the sign conventions considered, the components are summed as follows:

$$F_v = P_t \sin \theta - P_x \cos \theta \tag{5}$$

$$F_h = -P_x \sin \theta - P_t \cos \theta \quad . \tag{6}$$

PILE-HEAD MOVEMENT AND PILE REACTION

In the preceding sections the movement of the pile head and the forces acting on the pile head have been defined. In this section relations between pile reaction and movement will be developed.

For computational purposes the pile shown in Fig. 11a may be simulated by the set of springs as shown in Fig. 11b. The springs will produce a force parallel to the pile axis, P_x, and a force acting perpendicular to the pile axis, P_t. The rotational spring will produce a moment about the pile top, M_t.

The forces produced by the springs will depend on the deflection of the springs. Since the springs are nonlinear the movement and reaction are not related by a single constant. It is assumed that curves can be obtained which show spring reaction as a function of deflection. In Fig. 12 a hypothetical set of load-deflection curves are drawn for a set of springs. If the curves are single valued then the spring reactions may be calculated for a particular deflection by

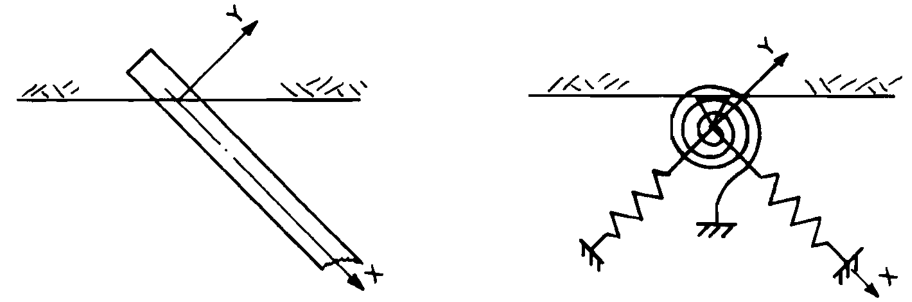
$$P_x = J_x \, x_t \tag{7}$$

$$P_t = J_y \, y_t \tag{8}$$

$$M_t = J_m \, y_t \tag{9}$$

where J_x, J_y, and J_m are the secant modulus values as illustrated in Fig. 12.

It should be noted that the moment produced by the rotational spring is proportional to the lateral deflection, rather than the rotation. For a rotational spring this procedure is inconsistent with usual concepts. This



a. Pile and foundation. b. Springs and foundation.

Fig. 11. Spring representation of pile.

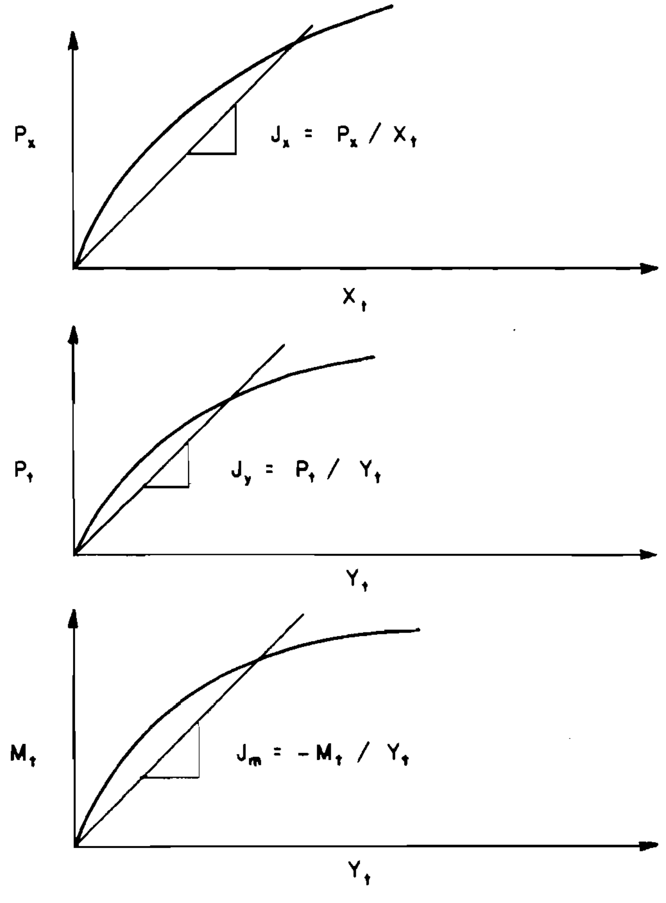


Fig. 12. Hypothetical spring load-deflection curves.

concept is used because it provides a convenient means for deriving and solving the equilibrium equation for the structure.

The curves shown in Fig. 12 do not adequately explain the behavior of a pile. It is not necessary that the exact nature of the curves be known. The representation shown is only for the formulation of the equilibrium equations. The procedure for calculating values for J_x, J_y, and J_m will be discussed in the following chapters. However, for the formulation of the equilibrium equations, Eqs. 7, 8, and 9 are sufficient, since they will be applicable no matter what kind of relationship exists between the loads and the displacements.

EQUILIBRIUM EQUATIONS

The relations between forces and movements for the structure and the pile have been developed in the preceding sections. In this section, these relations will be combined to form three equations of equilibrium for the structure. The form of the equations is such that an iterative type solution may be used. This is necessary since the system is nonlinear.

Consider a foundation supported by n piles. The coordinate system and the ith pile are shown in Fig. 13. The external loads applied to the foundation are resolved into the forces and moment through and about the origin of the coordinates as shown in Fig. 13. The forces and moment exerted by each pile are shown as F_{vi}, F_{hi}, and M_{si} in Fig. 13. The three equations are obtained by summing forces in the horizontal and vertical directions and by summing moments about the origin of the a-b coordinate system. Performing these operations the equilibrium equations may be written as

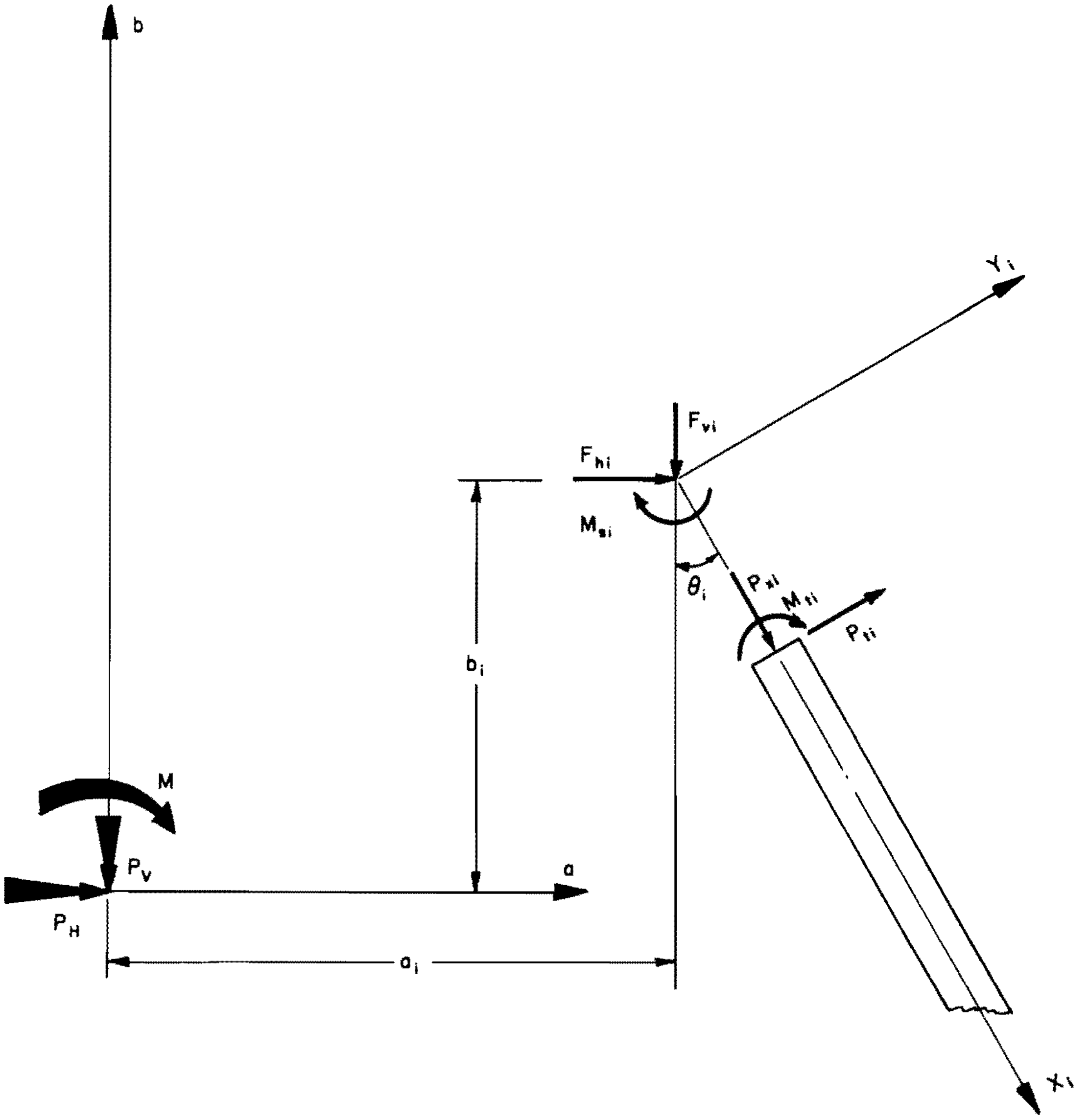


Fig. 13. Forces on the piles and foundation.

$$\sum_{i=1}^{n} F_{vi} + P_V = 0 \qquad (10)$$

$$\sum_{i=1}^{n} F_{hi} + P_H = 0 \qquad (11)$$

$$\sum_{i=1}^{n} (M_{si} + a_i F_{vi} + b_i F_{hi}) + M = 0 \ . \qquad (12)$$

Substituting Eqs. 4, 5, and 6 into Eqs. 10, 11, and 12 and rearranging

$$P_V = \sum_{i=1}^{n} (P_{xi} \cos \theta_i - P_{ti} \sin \theta_i) \qquad (13)$$

$$P_H = \sum_{i=1}^{n} (P_{ti} \cos \theta_i + P_{xi} \sin \theta_i) \qquad (14)$$

$$M = \sum_{i=1}^{n} \Big[M_{ti} + a_i (P_{xi} \cos \theta_i - P_{ti} \sin \theta_i) + b_i (P_{ti} \cos \theta_i + P_{xi} \sin \theta_i) \Big] \ . \qquad (15)$$

Substituting Eqs. 7, 8, and 9 into Eqs. 13, 14, and 15 the equilibrium equations may be written as

$$P_V = \sum_{i=1}^{n} (J_{xi} x_{ti} \cos \theta_i - J_{yi} y_{ti} \sin \theta_i) \qquad (16)$$

$$P_H = \sum_{i=1}^{n} (J_{yi} y_{ti} \cos \theta_i + J_{xi} x_{ti} \sin \theta_i) \qquad (17)$$

$$M = \sum_{i=1}^{n} \Big[- J_{mi}\, y_{ti} + a_i\, (J_{xi}\, x_{ti} \cos \theta_i - J_{yi}\, y_{ti} \sin \theta_i)$$

$$+ b_i\, (J_{yi}\, y_{ti} \cos \theta_i + J_{xi}\, x_{ti} \sin \theta_i) \Big] \; . \qquad (18)$$

The equations are modified further by substituting Eqs. 2 and 3 into Eqs. 16, 17, and 18 and rearranging to obtain

$$P_V = \sum_{i=1}^{n} \Bigg\{ \Big[J_{xi} \cos^2\theta_i + J_{yi} \sin^2\theta_i \Big] \Delta V + \Big[(J_{xi} - J_{yi}) \sin\theta_i \cos\theta_i \Big] \Delta H$$

$$+ \Big[a_i (J_{xi} \cos^2\theta_i + J_{yi} \sin^2\theta_i) + b_i (J_{xi} - J_{yi}) \sin\theta_i \cos\theta_i \Big] \alpha \Bigg\}$$

$$(19)$$

$$P_H = \sum_{i=1}^{n} \Bigg\{ \Big[(J_{xi} - J_{yi}) (\sin\theta_i \cos\theta_i) \Big] \Delta V + \Big[J_{yi} \cos^2\theta_i + J_{xi} \sin^2\theta_i \Big] \Delta H$$

$$+ \Big[a_i (J_{xi} - J_{yi}) \sin\theta_i \cos\theta_i + b_i (J_{yi} \cos^2\theta_i + J_{xi} \sin^2\theta_i) \Big] \alpha \Bigg\} \qquad (20)$$

$$M = \sum_{i=1}^{n} \Bigg\{ \Bigg[J_{mi} \sin \theta_i + a_i\, (J_{xi} \cos^2 \theta_i + J_{yi} \sin^2 \theta_i)$$

$$+ b_i\, (J_{xi} - J_{yi}) \sin \theta_i \cos \theta_i \Bigg] \Delta V + \Bigg[-J_{mi} \cos \theta_i$$

$$+ a_i (J_{xi} - J_{yi}) \sin\theta_i \cos\theta_i + b_i (J_{yi} \cos^2\theta_i + J_{xi} \sin^2\theta_i) \Bigg] \Delta H$$

$$+ \Bigg[J_{mi}\, (a_i \sin\theta_i - b_i \cos\theta_i) + a_i^2 (J_{xi} \cos^2\theta_i + J_{yi} \sin^2\theta_i)$$

$$+b_i^2(J_{yi}\cos^2\theta_i+J_{xi}\sin^2\theta_i)+2(J_{xi}-J_{yi})(\sin\theta_i\cos\theta_i)a_ib_i\Big] \quad \alpha \Bigg\} . \qquad (21)$$

Equations 19, 20, and 21 constitute the complete set of equilibrium equations for a foundation. The loads on the foundation, the distance to the pile tops, and the batter of the piles are known quantities. If the spring modulus values are known, the three equations may be solved simultaneously for ΔV, ΔH, and α. But, since the system is nonlinear, J_m, J_x, and J_y will not be constants. Because of this an iterative solution is required. Chapter IV will present methods for handling the behavior of the individual piles. Chapter V will give a brief summary of the iterative procedure used in the computer program for solving the equilibrium equations.

CHAPTER IV

BEHAVIOR OF INDIVIDUAL PILES

In the preceding chapter equilibrium equations were developed for a pile supported foundation. These equilibrium equations contain secant modulus values obtained from the nonlinear load-deformation curves for individual piles. This chapter deals with the methods used for obtaining the secant modulus values for the individual piles.

The modulus J_x is obtained from the axial behavior of the pile. Modulus values J_m and J_y are obtained from the lateral behavior of the pile.

AXIAL BEHAVIOR

In order that a value for J_x be calculated, an axial load-deflection relation is necessary. The procedure employed involves finding a load-settlement curve for the pile. A typical load-settlement curve is shown in Fig. 14. The curve shown consists of two branches, corresponding to bearing and pullout of the pile.

If a load-settlement curve is available, a value of secant modulus may be obtained for any value of axial deflection by applying Eq. 7. This is a simple procedure for obtaining J_x after the correct value for axial deflection is found. The problem which arises is to find a load-settlement curve which will accurately describe the axial behavior of a pile. Earlier methods of analysis did not require that an exact load-settlement curve be found. A computed ultimate axial load, or an ultimate load obtained from a full scale load test was usually considered adequate for design purposes. For the proposed method, a relationship between load and deflection is necessary. The

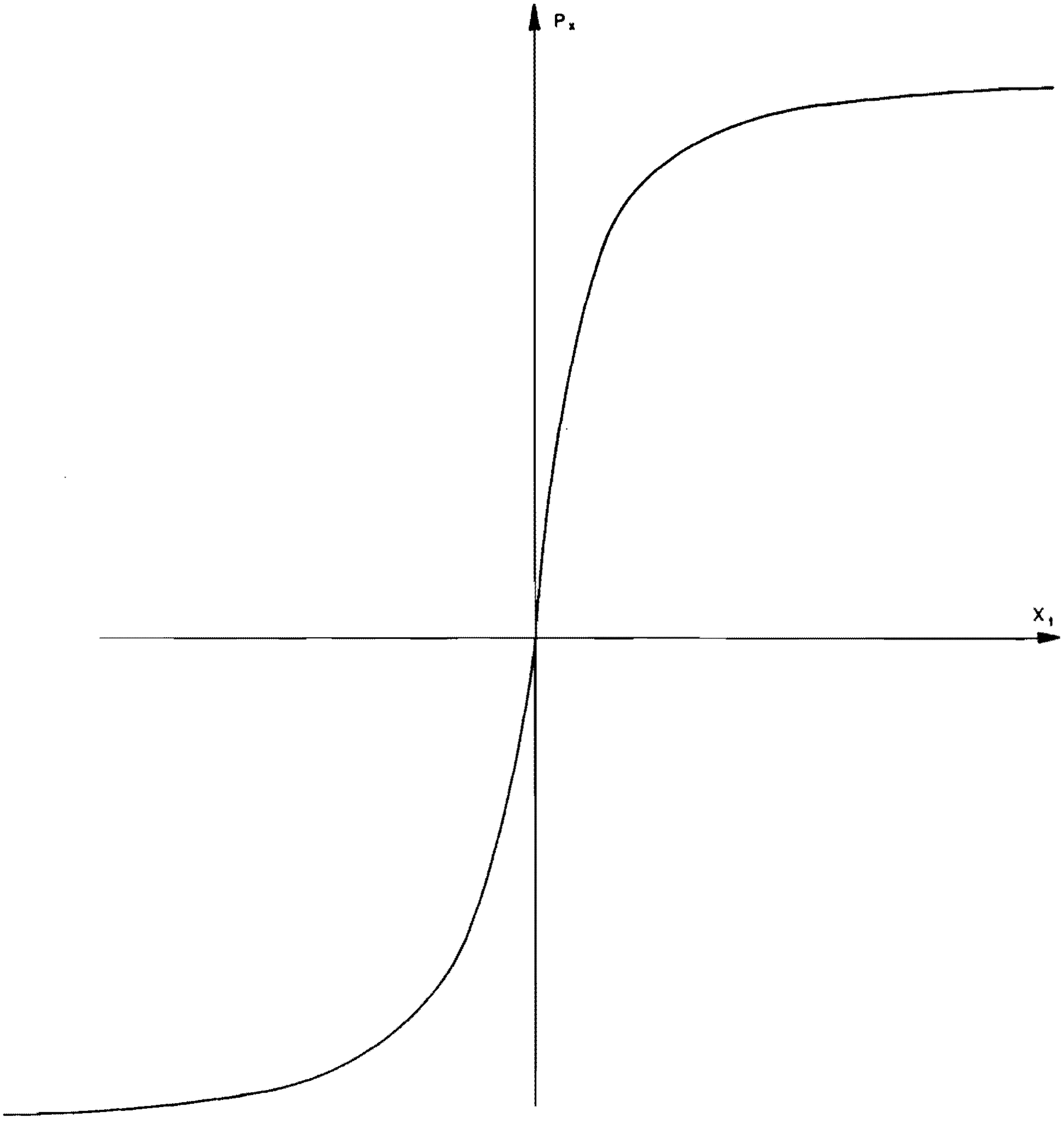


Fig. 14. Axial load-settlement curve.

axial behavior of piles is usually determined by one of three methods. These are as follows:

1. Dynamic formulas
2. Static formulas
3. Full scale loading test.

Dynamic Formulas

Dynamic formulas such as that of Hiley as described by Chellis[2] give only a maximum pile capacity with no regard to corresponding movements. It has been demonstrated that the dynamic formulas give very erratic results with poor correlation between calculated and measured values of pile capacity[3,13]. The various formulas have limited usefulness for the method considered because of the lack of load-settlement data.

Static Formulas

The static formulas relate the load carrying capacity of the pile to the soil properties. The usual procedure is to calculate a tip load using some bearing capacity formula, such as that suggested by Meyerhof[11,12], and some shaft load which is transferred to the soil through skin friction along the pile. Accurate prediction of skin friction is difficult but suggested values are available[2]. The bearing capacity and shaft load are added to obtain the total pile capacity. This method is also limited by the lack of load-settlement data. If the dynamic and static formulas are to be of any value to the analysis under consideration, some method must be found to relate load to deflection.

The method proposed by Reese[16] seems to offer a great deal of promise for predicting load-settlement curves from soil data. Coyle[4] has compared measured values with values calculated using this method, for steel friction piles in clay. The correlation obtained was quite good. However, the usefulness of this method is limited by the lack of correlation for a range of pile and soil types.

Full Scale Loading Test

The use of loading tests is the most reliable method presently available for predicting load-settlement curves. A pullout test and a bearing test will give the desired load-deflection relation.

Conclusions

Of the methods discussed, the loading test gives results which best represent the axial behavior of a pile. The method suggested by Reese[16] will give reliable results provided the load transfer can be accurately predicted. The static and dynamic formulas have limited usefulness because of the lack of load-deflection information. A load-deflection curve may be obtained by assuming some relation between load and deflection based on the calculated ultimate load. The accuracy of this procedure will depend on the accuracy of the assumption, and it will probably give only a rough estimate.

LATERAL BEHAVIOR

For the calculation of the modulus value J_y a relationship between the shear at the top of the pile and the lateral deflection of the pile top must be known. For the calculation of J_m some relationship between moment at the top of the pile and top deflection must be known. In the preceding section, on the calculation of J_x, a load-deflection curve was used. This is possible since it is assumed that the axial behavior of the pile is unaffected by any lateral effects. That is to say that the axial load on the pile is dependent only on the axial deflection of the pile. A similar assumption concerning lateral behavior is not true. Simple single-valued curves for P_t vs. y_t and M_t vs. y_t as shown in Fig. 12 do not exist for a pile which is attached to a foundation.

Since a single-valued load-deflection relationship cannot be found, a different approach must be taken for calculating J_m and J_x. The approach taken involves the solution for the deflected shape of the pile using finite difference equations. Once the deflected shape is known the shear and moments can be calculated and modulus values may then be calculated using Eqs. 8 and 9. The interaction is nonlinear so that an iterative process must be employed to find the correct modulus values. The iterative procedure will be explained in detail in Chapter V. For the following discussion assume that the iterative procedure is complete and that correct boundary conditions are applied to the pile. With this in mind the finite difference solution for the laterally loaded pile will be discussed and the calculation of the modulus value explained. The soil criteria used to determine the lateral interaction will also be explained.

Finite Difference Solution for Laterally Loaded Piles

The finite difference approach to the solution of laterally loaded piles was first suggested by Gleser[6]. This idea was further extended by Reese and Matlock[9,17]. The method presented here is for the special case of a laterally loaded pile and is similar to the method presented in Refs. 9 and 17, the differences being in the application of boundary conditions and the addition of the effects of axial load on the lateral deflection.

The differential equations are derived by considering an element of the pile as shown in Fig. 15. The sign of all forces, deflections, and slopes shown are positive. It should also be noted that the axial load is constant over the length of the pile. For piles this assumption is not consistent

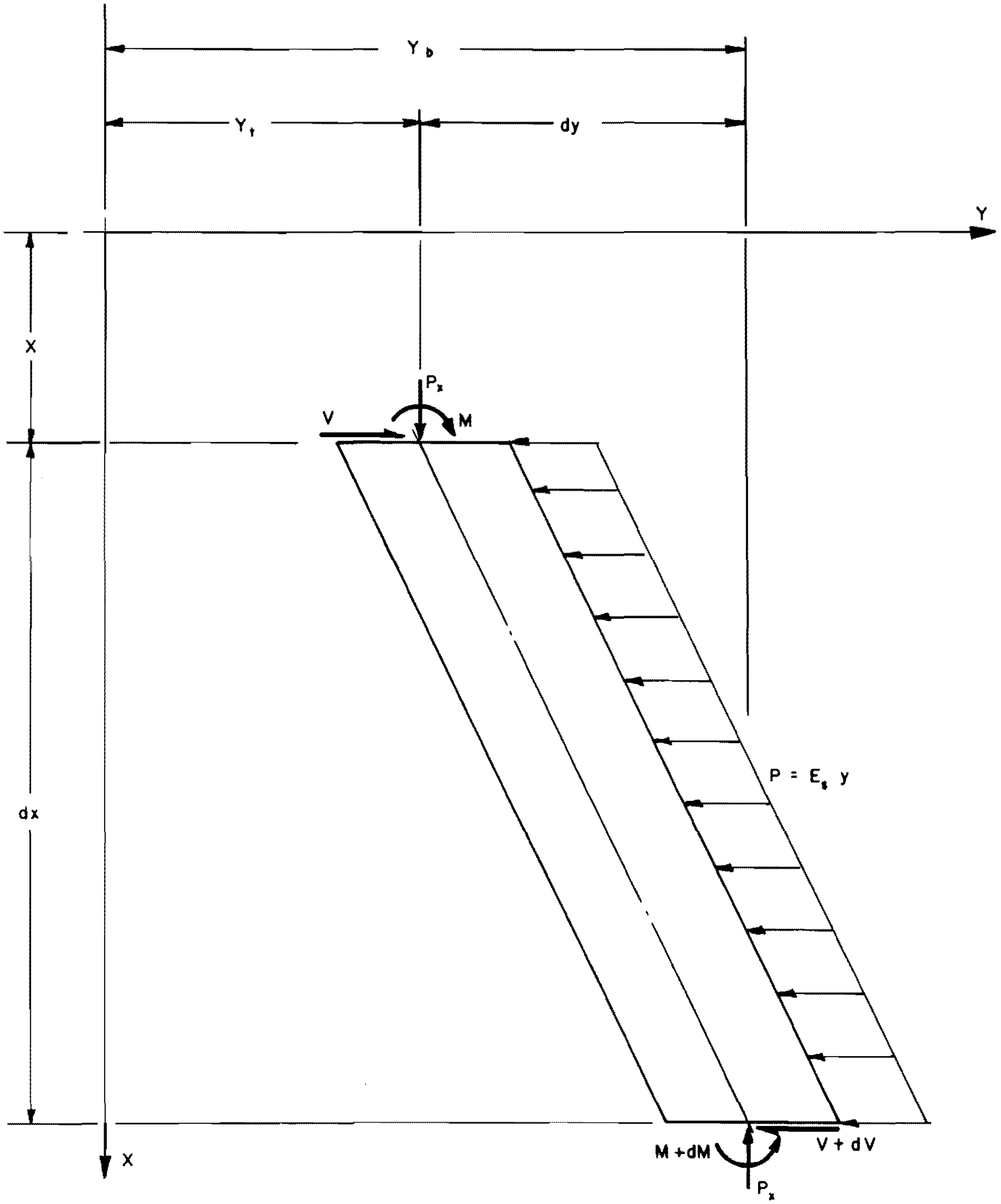


Fig. 15. Generalized beam column element.

with observed behavior, since it is known that some of the applied axial load is transferred to the soil by skin friction along the shaft. The validity of this assumption is based on the fact that the errors introduced will be insignificant. Considering the problem from a physical standpoint it is known that for most cases the skin friction increases with depth. This, plus the fact that any lateral movement will cause a decrease in skin friction, leads to the conclusion that the axial load removed by the skin friction in the upper portion of the pile is small. Since the maximum moment occurs in the top portion of the pile, and since it is the deflection of the pile top which is of interest, the assumption of constant axial load will not significantly affect the results of interest.

The reason for having the assumption of axial load constant on the top of the pile is one of convenience. The addition of a variable axial load could have been handled analytically but the effort required for obtaining a solution would not be warranted because of uncertainties involved in obtaining the nature of the variation.

Referring to Fig. 15 the equilibrium equations for the element may be written as

$$\frac{dM}{dx} - V + P_x \frac{dy}{dx} = 0 \tag{22}$$

and

$$\frac{dV}{dx} = - p = - E_s \, y \tag{23}$$

where

M = Bending moment

x = Distance along pile

V = Shear

P_x = Axial load (constant)

y = Lateral deflection

p = Soil reaction per unit length

E_s = Soil modulus.

By combining Eqs. 22 and 23 and differentiating, the following equation is obtained:

$$\frac{d^2M}{dx^2} + E_s\, y + P_x \frac{d^2y}{dx^2} = 0 \quad . \tag{24}$$

The equation for shear is written as

$$V = \frac{dM}{dx} + P_x \frac{dy}{dx} \tag{25}$$

and the equation for moment is written as

$$M = EI \frac{d^2y}{dx^2} = R \frac{d^2y}{dx^2} \tag{26}$$

where

E = Modulus of elasticity of the pile

I = Moment of inertia of pile section

R = EI (flexural rigidity).

Equations 24, 25, and 26 may be written in finite difference form using the central-difference approximations. The equations will be written for a general point referred to as station "i". Station numbering increases from top to bottom of piles. The equations obtained for station "i" are as follows:

$$y_{i+2}(R_{i+1}) + y_{i+1}(-2R_{i+1} - 2R_i + P_x h^2) + y_i(R_{i+1} + 4R_i + R_{i-1} - 2P_x h^2 + E_{si} h^4) + y_{i-1}(-2R_i - 2R_{i-1} + P_x h^2) + y_{i-2}(R_{i-1}) = 0 \tag{27}$$

$$V_i = \frac{1}{2h^3}\left[y_{i+2}(R_{i+1}) + y_{i+1}(-2R_{i+1} + P_x h^2) + y_i(R_{i+1} - R_{i-1}) + y_{i-1}(2R_{i-1} - P_x h^2) + y_{i-2}(-R_{i-1})\right] \tag{28}$$

$$M_i = R_i\left(\frac{y_{i+1} - 2y_i + y_{i-1}}{h^2}\right) \tag{29}$$

where

h = Increment length.

The finite difference equations are used to obtain the deflected shape of the pile. Once the deflected shape is obtained any other information about the pile may be obtained by the application of the appropriate equations.

The pile is divided into "n" increments of length "h" as shown in Fig. 16. In addition, two fictitious increments are added to the top and bottom of the pile. The four fictitious stations are added for formulating the set of equations but they will not appear in the final set of equations. The coordinate system and numbering system used is illustrated in Fig. 16.

The procedure used is to write Eqs. 27, 28, and 29 about station n+3. This results in 3 equations involving 5 unknown deflections (y_{n+5}, y_{n+4}, y_{n+3}, y_{n+2}, y_{n+1}). Two boundary conditions, $V_{n+3} = 0$ and $M_{n+3} = 0$, are applied at station n+3. The deflections for the fictitious stations n+4 and n+5 are eliminated from the three equations and the

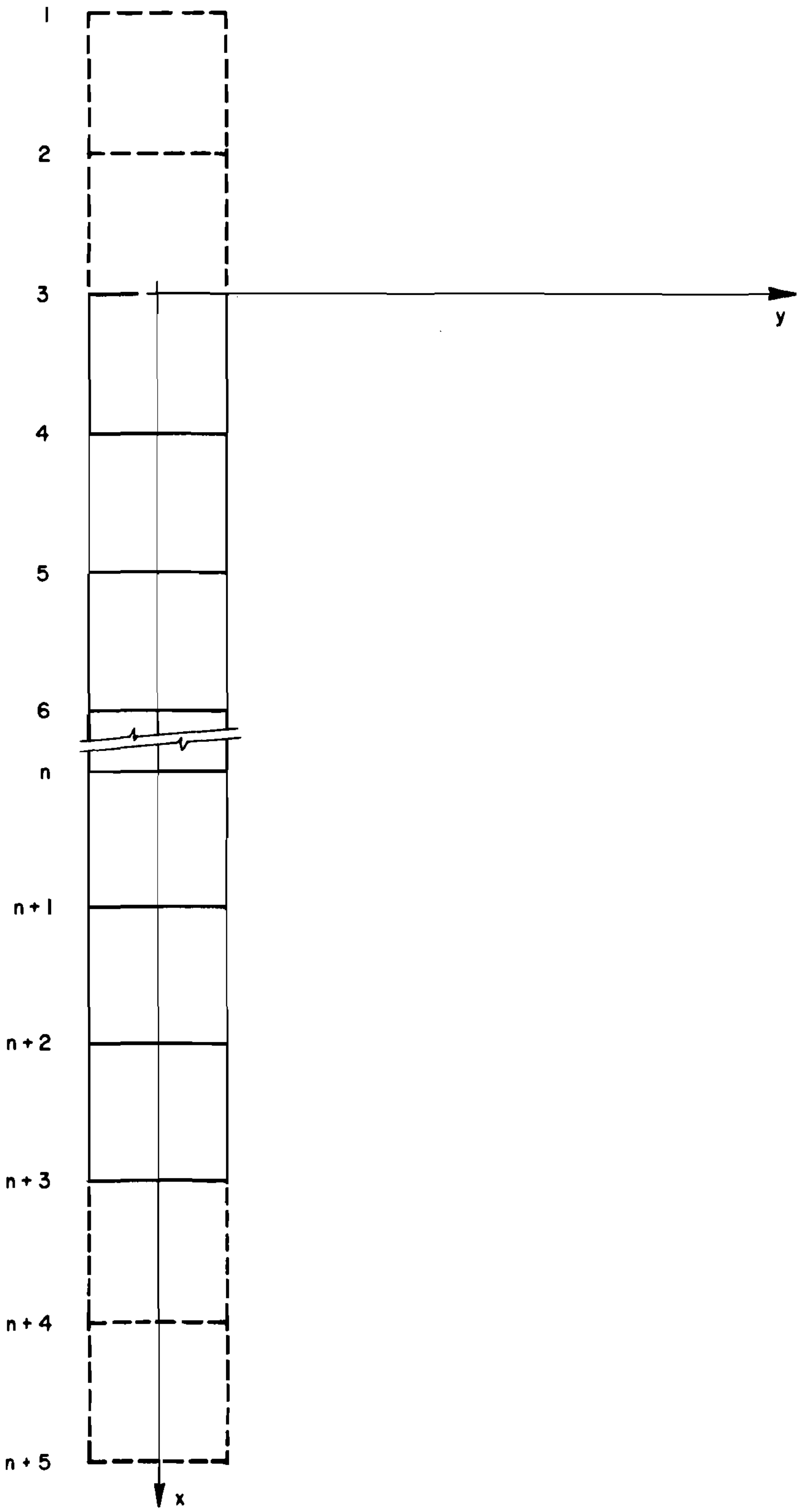


Fig. 16. Finite difference representation of pile.

deflection for station n+3 is found in terms of the deflection at stations n+2 and n+3. The equation obtained may be written as:

$$y_{n+3} = A_{n+3}\, y_{n+2} - B_{n+3}\, y_{n+1} \tag{30}$$

where

$$A_{n+3} = \frac{4R_{n+2} - 2P_x h^2}{2R_{n+2} - 2P_x h^2 + E_{s(n+3)} h^4} \tag{31}$$

and

$$B_{n+3} = \frac{2R_{n+2}}{2R_{n+2} - 2P_x h^2 + E_{s(n+3)} h^4} \quad . \tag{32}$$

Equation 27 is written for station n+2. This equation is combined with Eqs. 28 and 29 for station n+3, and Eq. 30 to determine the deflection for station n+2. The deflection y_{n+2} is found in terms of the deflection of stations n+1 and n. The equation obtained is as follows:

$$y_{n+2} = A_{n+2}\, y_{n+1} - B_{n+2}\, y_n \tag{33}$$

where

$$A_{n+2} = \frac{2R_{n+1} + (2R_{n+2} - P_x h^2)(1 - B_{n+3})}{R_{n+1} + (2R_{n+2} - P_x h^2)(2 - A_{n+3}) + E_{s(n+2)} h^4} \tag{34}$$

and

$$B_{n+2} = \frac{R_{n+1}}{R_{n+1} + (2R_{n+2} - P_x h^2)(2 - A_{n+3}) + E_{s(n+2)} h^4} \quad . \tag{35}$$

The deflection for station n+1 may be found in a similar manner. From station n+1 to the top of the pile the expressions for the deflection have the same form. The general form of the equation is as follows:

$$y_i = A_i \, y_{i-1} - B_i \, y_{i-2} \tag{36}$$

where

$$A_i = \frac{2R_{i-1} + R_i(2-2B_{i+1}) + R_{i+1}(A_{i+2} \, B_{i+1} - 2B_{i+1}) - P_x h^2(1-B_{i+1})}{C_i} \tag{37}$$

$$B_i = \frac{R_{i-1}}{C_i} \tag{38}$$

and

$$\begin{aligned} C_i = {} & R_{i-1} + R_i(4 - 2A_{i+1}) + R_{i+1}(A_{i+1} \, A_{i+2} - B_{i+2} - 2A_{i+1} + 1) \\ & - P_x h^2(2 - A_{i+1}) + E_{si} h^4 \quad . \end{aligned} \tag{39}$$

With the general expression the deflection of each station may be expressed as a function of the deflection of the two stations immediately above it. If the deflections for stations 3, 4, and 5 are written a set of three equations involving five unknown deflections will be obtained. If two boundary conditions are introduced the deflections for the fictitious stations may be eliminated and the equations solved for the deflections. Once the deflections for stations 3 and 4 are found the deflections for the remainder of the pile may be obtained by back substitution into the equations obtained for the deflection of a station in terms of the deflection of the two stations directly above it.

The expressions obtained for y_3 and y_4 will depend on the boundary conditions applied to the top of the pile. Three sets of boundary conditions are used resulting in three sets of equations.

For the first case the following boundary conditions are applied:

$$M_3 = M_t \tag{40}$$

$$V_3 = P_t \tag{41}$$

where M_t and P_t are the moment and lateral load applied to the top of the pile. The application of these boundary conditions results in the following expressions for y_3 and y_4:

$$\begin{aligned} y_3 = & \left\{\left[D_2 \left[R_4 (2 A_5 B_4 - 4 B_4) + R_3 (2 - 2 B_4) + 2P_x h^2 B_4\right]\right.\right. \\ & \left.\left. + D_3 G_2\right]\right\} \Big/ \left\{\left[G_1 \left[R_3 (2 B_4 - 2) + R_4 (4 B_4 - 2 A_5 B_4)\right.\right.\right. \\ & \left. - 2P_x h^2 B_4\right] + G_2 \left[R_3 (4 - 2 A_4) + R_4 (2 A_4 A_5\right. \\ & \left.\left.\left. - 2 B_5 - 4 A_4 + 2) + P_x h^2 (- 2 + 2 A_4) + E_{s3} h^4\right]\right]\right\} \end{aligned} \tag{42}$$

$$y_4 = y_3 \left(A_4 - \frac{B_4 G_1}{G_2}\right) - \frac{B_4 D_2}{G_2} \tag{43}$$

where

$$D_2 = \frac{M_t h^2}{R_3} \tag{44}$$

$$D_3 = 2P_t h^3 \tag{45}$$

$$G_1 = 2 - A_4 \tag{46}$$

$$G_2 = 1 - B_4 \ . \tag{47}$$

The second set of boundary conditions applied are as follows:

$$V_3 = P_t \tag{41}$$

$$\left(\frac{dy}{dx}\right)_3 = \frac{y_4 - y_2}{2h} = S_t \ . \tag{48}$$

These boundary conditions result in the following expressions for y_3 and y_4:

$$y_3 = \left\{ D_3 \ (1 + B_4) + D_4 \left[2 \ R_4 \ (2 \ B_4 - A_5 \ B_4) + 2 \ R_3 \ (B_4 - 1) - 2P_x h^2 \ B_4 \right] \right\} \Big/ \left\{ 2 \ R_4 \left[A_4 \ A_5 - B_5 - B_4 \ B_5 - 2 \ A_4 + 1 + B_4 \right] + 4 \ R_3 \ (1 - A_4 + B_4) + 2P_x h^2 \ (A_4 - B_4 - 1) + E_{s3} h^4 \right\} \tag{49}$$

$$y_4 = y_3 \left(\frac{A_4}{1 + B_4}\right) + \frac{B_4 \ D_4}{1 + B_4} \tag{50}$$

where

$$D_4 = 2S_t h \ . \tag{51}$$

The third set of boundary conditions applied are as follows:

$$V_3 = P_t \tag{41}$$

$$M_3 / S_3 = M_t / S_t \ . \tag{52}$$

These boundary conditions result in the following expressions for y_3 and y_4:

$$\begin{aligned} y_3 = D_3 \left[1 - B_4 + D_5(1 + B_4)\right] \Big/ \Big\{ & 2\ D_5\ (2\ R_3 + 2\ R_3\ B_4 \\ & - 2\ R_3\ A_4 + R_4\ A_4\ A_5 - R_4\ B_4\ B_5 - 2\ R_4\ A_4 \\ & + R_4 + R_4\ B_4) + 2\ R_4\ (A_4\ A_5 - 2\ A_5\ B_4 - B_5 \\ & + B_4\ B_5 - 2\ A_4 + 3\ B_4 + 1) + 2P_x h^2\ (A_4 - B_4 - 1 \\ & + A_4\ D_5 - D_5 - B_4\ D_5) + E_{s3} h^4 \left[1 - B_4 + D_5\ (1 + B_4)\right] \Big\} \end{aligned} \tag{53}$$

$$y_4 = \left[A_4 - \frac{B_4\ (2 - A_4 + A_4\ D_5)}{(1 + D_5 - B_4 + B_4\ D_5)}\right] y_3 \tag{54}$$

where

$$D_5 = \frac{M_t}{S_t} \left(\frac{h}{2\ R_3}\right) \quad . \tag{55}$$

When the first set of boundary conditions is used the calculation of J_y and J_m involves only the application of Eqs. 8 and 9. The moment and lateral load applied are divided by the calculated deflection of the pile top.

When the second and third sets of boundary conditions are used the moment applied must be calculated. This is obtained by applying the following equation:

$$M_3 = \frac{R_3}{h^2} \left[y_3 \left(\frac{A_4}{B_4} - 2\right) + y_4\ (1 - 1/B_4)\right] \quad . \tag{56}$$

Since the lateral load is known the modulus values may be obtained.

Lateral Soil-Pile Interaction

In the preceding section the effect of the soil on the pile was shown as a distributed reaction p. The soil reaction p was defined as:

$$p = E_s y \quad . \tag{23}$$

where E_s is the soil modulus and y is the lateral deflection. The soil reaction resists the deflection of the pile. For the derivation of the finite difference equations it was assumed that the soil modulus values were known. Since the soil-pile interaction is usually nonlinear an iterative procedure is required to find the correct values of E_s. The following discussion deals with the development of the relationship between lateral pile movement and soil reaction. In the final section of this chapter the soil criteria used will be discussed.

A typical relation between p and y is shown in Fig. 17. The soil modulus is defined by Eq. 23. From Fig. 17 it is seen that the soil modulus is the slope of the secant drawn from the origin to any point along the curve. Since p is defined as the distributed soil reaction with units of force per unit of length along the pile the soil modulus E_s will have units of force per unit length squared. Since the p-y curve for most soils is nonlinear, an iterative procedure will usually be required to find the correct soil modulus, and the corresponding deflected shape.

The p-y curves will depend on the soil properties. For most cases the properties of the soil in a profile is not constant with depth. The usual case being that the strength of the soil increases with depth. A typical variation of shear strength of soil with depth is shown in Fig. 18a. Since the strength of the soil will affect the p-y curves obtained, a variation similar to that illustrated in Fig. 18b might be expected. It should be

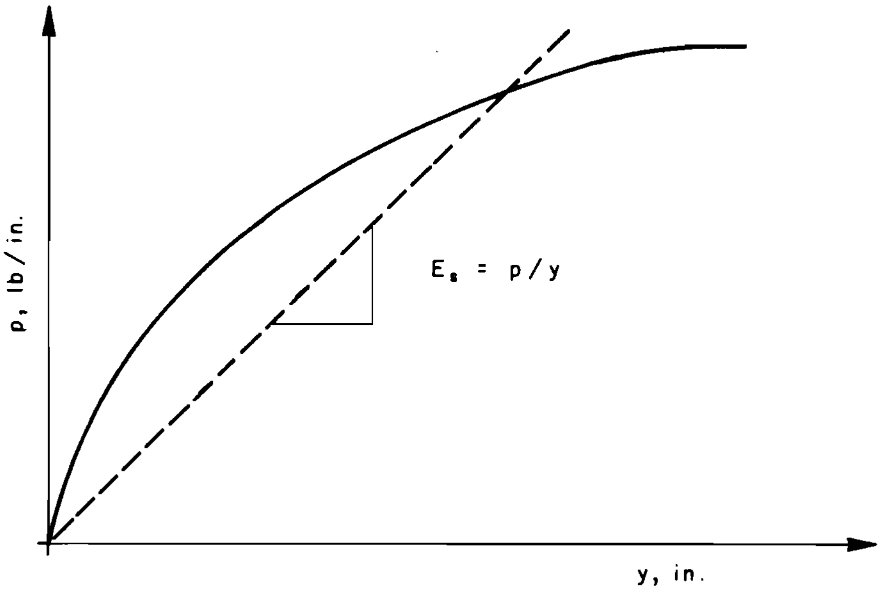
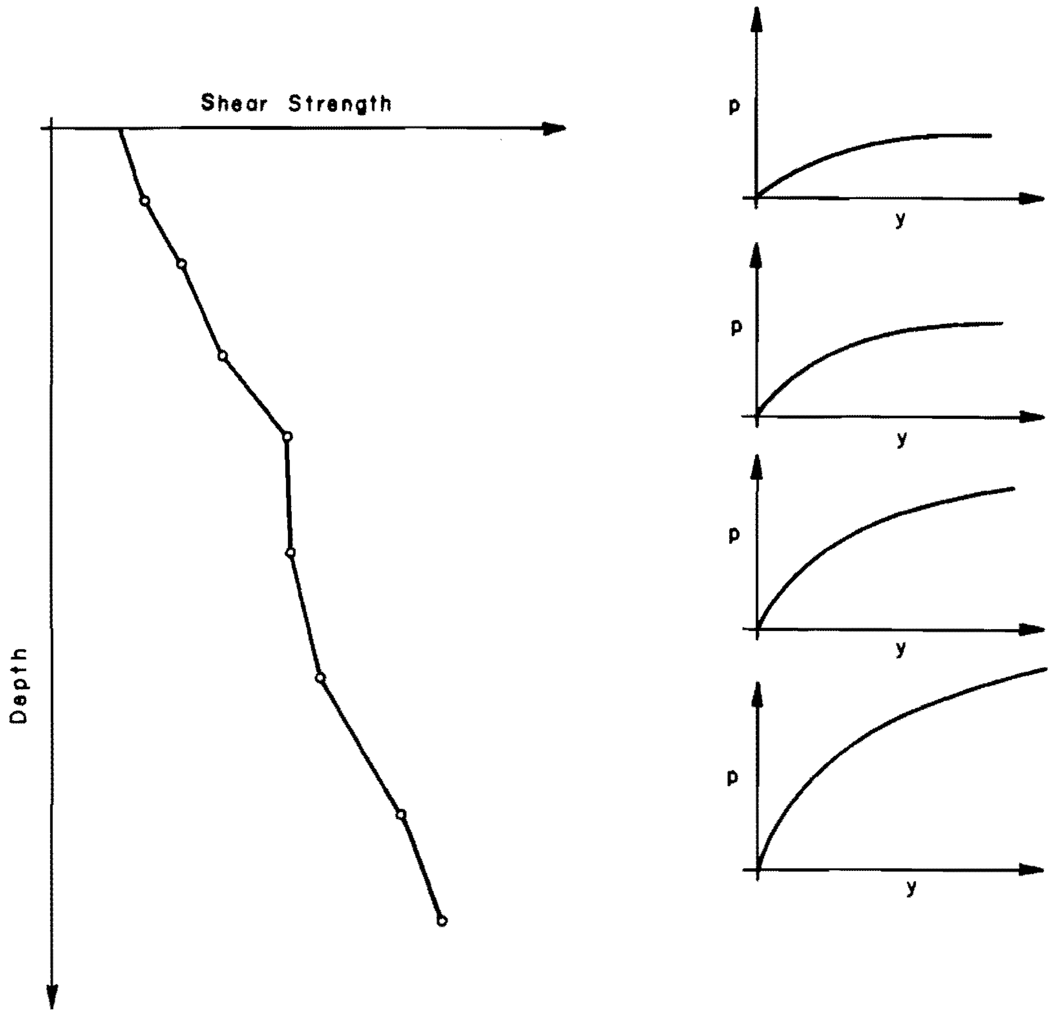


Fig. 17. Typical p-y curve.



a. Variation of shear strength with depth.

b. Variation of p-y curves with depth.

Fig. 18. Variation of soil properties with depth.

pointed out that the shear strength is not the only parameter which will affect the p-y curve, although it does have considerable influence. The purpose of the variation shown in Fig. 18b is only to illustrate the variability of the p-y relation.

For use in the equations for deflection a value of soil modulus is required for each station. If a p-y curve is available at a station and the deflection is known, then a value for soil modulus can be obtained. If a p-y curve is not available for a particular station, then a soil modulus value is obtained by linear interpolation between p-y curves above and below the particular station. The E_s values obtained are used in the solution for the deflections. The iterative process is continued until closure is obtained for the deflections.

Soil Criteria

The soil criteria presented here for obtaining p-y curves is derived from theoretical and empirical considerations. It is limited by the fact that criteria is available only for clay and sand. No criteria is available for soil which has cohesion and also some angle of internal friction. It must also be used with reservation since sufficient correlation with measured values is not available. Work of this nature has been done but it is still confidential information. Once this information becomes available to the engineering profession it will be possible to obtain more realistic p-y curves, than are obtainable from the theory presented.

It is assumed that the p-y curves can be divided into two segments. The portion designated as 0-A and the portion designated as A-B in Fig. 19. The segment 0-A represents the early part of the curve and the segment A-B represents the ultimate part of the curve. Because of this division the construction of p-y curves may be carried out in two steps. First the

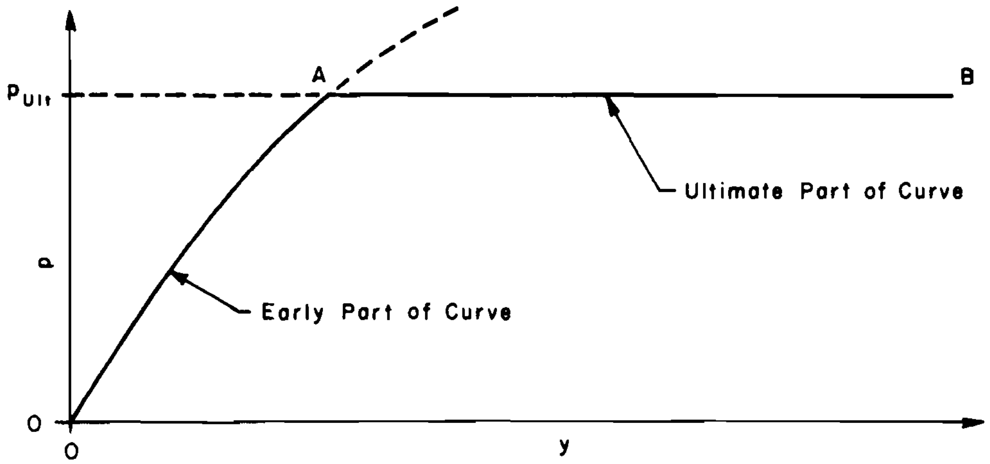


Fig. 19. Construction of p-y curve.

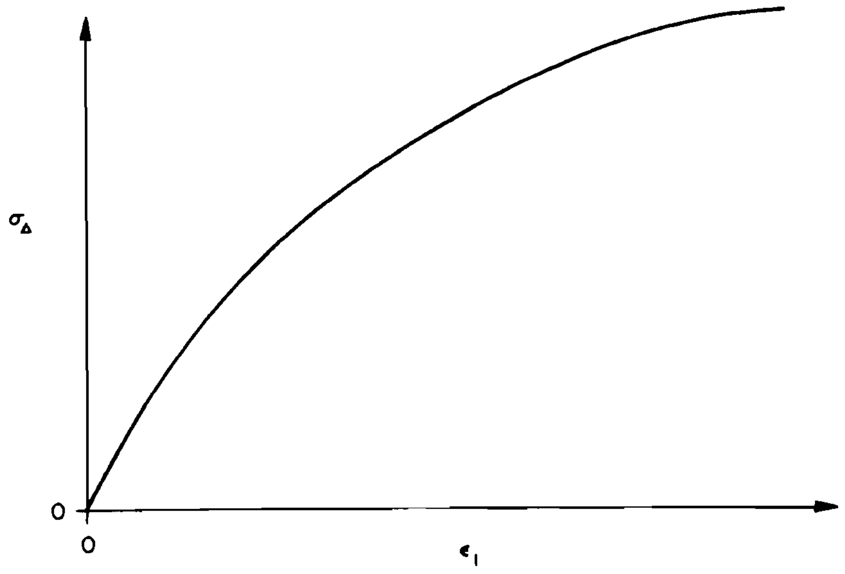


Fig. 20. Stress-strain curve.

ultimate soil resistance is calculated and then the shape of the early part of the curve is obtained. The horizontal line representing the ultimate soil resistance and the early part of the curve are then joined to form a continuous curve. In the following sections the procedure will be explained for clay and then sand.

For clay two methods are employed to obtain p-y curves. If stress-strain data are available the method proposed by Bramlette McClelland and John A. Focht, Jr.[10] is used, with one modification. For this method stress-strain curves similar to the one shown in Fig. 20 are required. The curve is obtained from a triaxial test in which the confining pressure σ_3 is as close as possible to the confining pressure on the soil in the field. McClelland and Focht recommend that the p-y curve be obtained by using the following relations:

$$p = 5.5\ w\ \sigma_\Delta \tag{57}$$

and

$$y = \tfrac{1}{2}\ w\ \varepsilon \tag{58}$$

where

w = Pile diameter or width

σ_Δ = Deviator stress $(\sigma_1 - \sigma_3)$

ε = Strain.

A. W. Skempton[20] has suggested the following relationship for calculating deflections of footings:

$$y = 2\ w\ \varepsilon\ . \tag{59}$$

It is felt that the best value to use for deflection would be one between the values calculated using Eqs. 58 and 59. The equation suggested is:

$$y = w\,\epsilon\ . \tag{60}$$

Using Eqs. 57 and 60 and the stress-strain curve a corresponding p-y curve may be obtained.

It is assumed that the test is run until failure is obtained. That is, the maximum value for σ_Δ obtained will represent the ultimate value which may be carried by the soil. Because of this, the value for p calculated using the ultimate value of σ_Δ is considered to be the ultimate soil resistance.

If no stress-strain curves are available, but the shear strength and unit weight are known, p-y curves can be obtained. Two expressions are available for calculating the ultimate soil resistance for clay. These equations were suggested by Reese[18] and are as follows:

$$p_{ult} = \gamma\, w\, X + 2\, c\, w + 2.83\, c\, X \tag{61}$$

and

$$p_{ult} = 11\, cw \tag{62}$$

where

γ = Unit weight

w = Pile diameter or width

X = Depth from soil surface

c = $q_u/2$ = Cohesion.

The smaller of the two values obtained from Eqs. 61 and 62 is used. Equation 61 will usually control near the surface since it is based on the occurrence of a wedge type failure and Eq. 62 will control at depth since it is based on the soil failing by flowing around the pile.

The early part of the curve is obtained by Eqs. 57 and 60. Since no stress-strain curve is available, values of σ_Δ and ϵ must be found. These are found by approximating the stress-strain curve. The following assumptions are made for drawing approximate stress-strain diagrams:

$\sigma_{\Delta 50} = c = q_u/2$

$\epsilon_{50} = 0.005$ (Brittle or stiff clays)

$\epsilon_{50} = 0.02$ (Soft plastic clay)

$\epsilon_{50} = 0.01$ (No consistency data available)

where

ϵ_{50} = 50% of elastic strain

$\sigma_{\Delta 50}$ = Deviator stress corresponding to 50% strain.

The value of $\sigma_{\Delta 50}$ and ϵ_{50} are plotted as shown in Fig. 21. A straight line with a slope of 0.5 is drawn through this point. This line represents the stress-strain curve for the soil. With this curve the early part of the curve may be obtained by applying Eqs. 57 and 60.

For sand the two equations for calculating the ultimate soil resistance are as follows:

$$p_{ult} = \gamma w X \left[\frac{\tan\beta}{\tan(\beta-\phi)} - K_A\right] + \gamma X^2 \left[\frac{\tan^2\beta\tan\alpha}{\tan(\beta-\phi)} + \frac{K_o\sin\beta\tan\phi}{\cos\alpha\tan(\beta-\phi)} + K_o\tan\beta\tan\phi\sin\beta - K_o\tan\beta\tan\alpha\right] \quad (63)$$

and

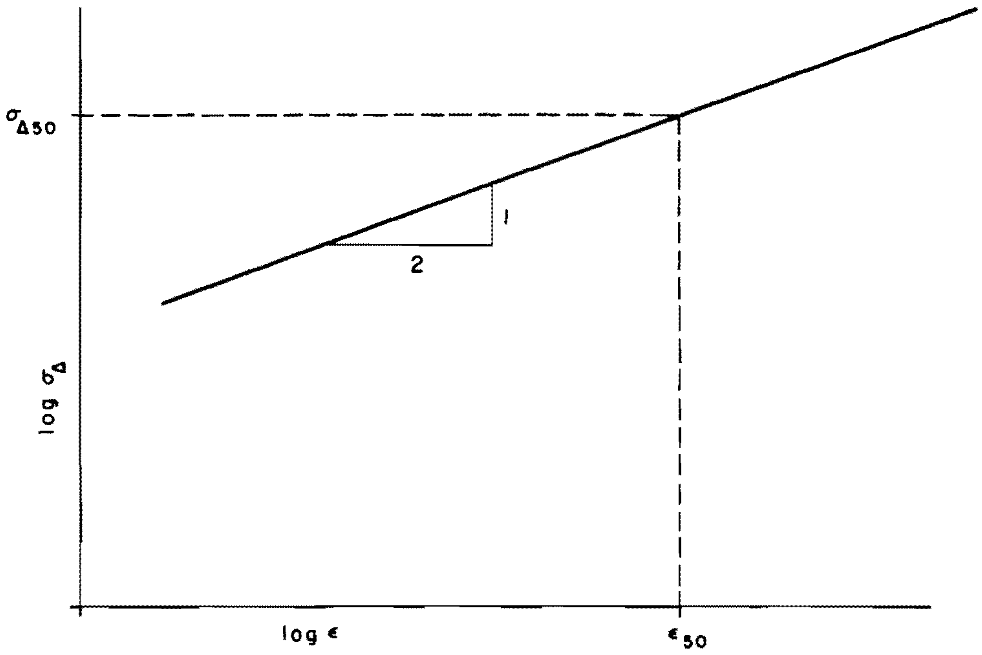


Fig. 21. Approximate log-log plot of stress-strain curve.

$$p_{ult} = \gamma w X \left\{ \tan^2 (45^\circ - \phi/2) \left[\tan^8 (45^\circ + \phi/2) - 1 \right] + K_0 \tan\phi \tan^4 (45^\circ + \phi/2) \right\} \qquad (64)$$

where

K_0 = Coefficient of earth pressure at rest

γ = Unit weight of sand

X = Depth

w = Pile diameter or width

ϕ = Angle of internal friction

$\beta = 45^\circ + \phi/2$

$\alpha = \phi/2$ to $\phi/3$ (loose sand)

$= \phi$ (dense sand).

Equation 63 is for wedge shaped failure and 64 is for flow around failure.

The early part of the curves are obtained by applying theory developed by Karl Terzaghi[22]. This results in a linear variation between p and y, with the slope given by Eq. 65.

$$S = \frac{A\,\gamma\,X}{1.35} \qquad (65)$$

S = Slope of early part of curve

A = Constant depending on relative density of sand.

Suggested values for A are 200 for loose sand, 600 for sand with medium density, and 1500 for dense sand. The unit weight used is the effective unit weight.

If the slope of the early part of the curve is known, the p-y curve can be constructed by connecting a straight line through the origin, with a slope defined by Eq. 65, to the horizontal line defined by the ultimate soil resistance. This results in a p-y curve which consists of two straight lines. When one considers the behavior of a sand it will be noted its behavior is not linear. Because of this the p-y curve obtained should be considered as an approximation.

Conclusions

In this chapter the behavior of a single isolated pile has been considered. The axial and lateral behavior of the pile was considered and the methods for calculating the spring modulus values explained. The soil criteria used for obtaining p-y curves was also considered. Certain limitations of the procedures used were discussed. Further limitations will be considered in Chapter VII.

CHAPTER V

COMPUTATIONAL PROCEDURE

BENT1 is a computer program written to solve problems involving pile supported foundations. It is a modification of programs developed previously at The University of Texas at Austin. It consists of an iterative solution for the three equilibrium equations developed in Chapter III using methods developed in Chapter IV to handle the nonlinear behavior of individual piles.

A general explanation of the computational scheme for the program will be presented in this chapter. Example problems are considered in Chapter VI. Detailed guides for preparing input data are given in Appendix A. A complete flow chart is given in Appendix B. A list of the notation used is given in Appendix C, and a complete listing of the program is given in Appendix D. Listings of the coded input and output for the example problems are given in Appendices E and F.

OUTLINE OF PROCEDURE FOR BENT1

The general procedure used for solution of the equilibrium equations is shown in Fig. 22. The purpose of the iterative procedure is to find the deflected position of the structure so that equilibrium and compatibility are satisfied. The procedure followed by the computer program is essentially that shown in Fig. 22. Rather than present a complete flow diagram for the program, the basic procedure employed will be described. It will be noted that the procedure described is essentially that shown in Fig. 22.

To begin the solution, input data for the problem are read in. The geometry of the foundation and the axial behavior of the piles are described. The lateral behavior of the piles may be described by inputing p-y curves, or soil properties may be input and p-y curves generated by SUBROUTINE MAKE.

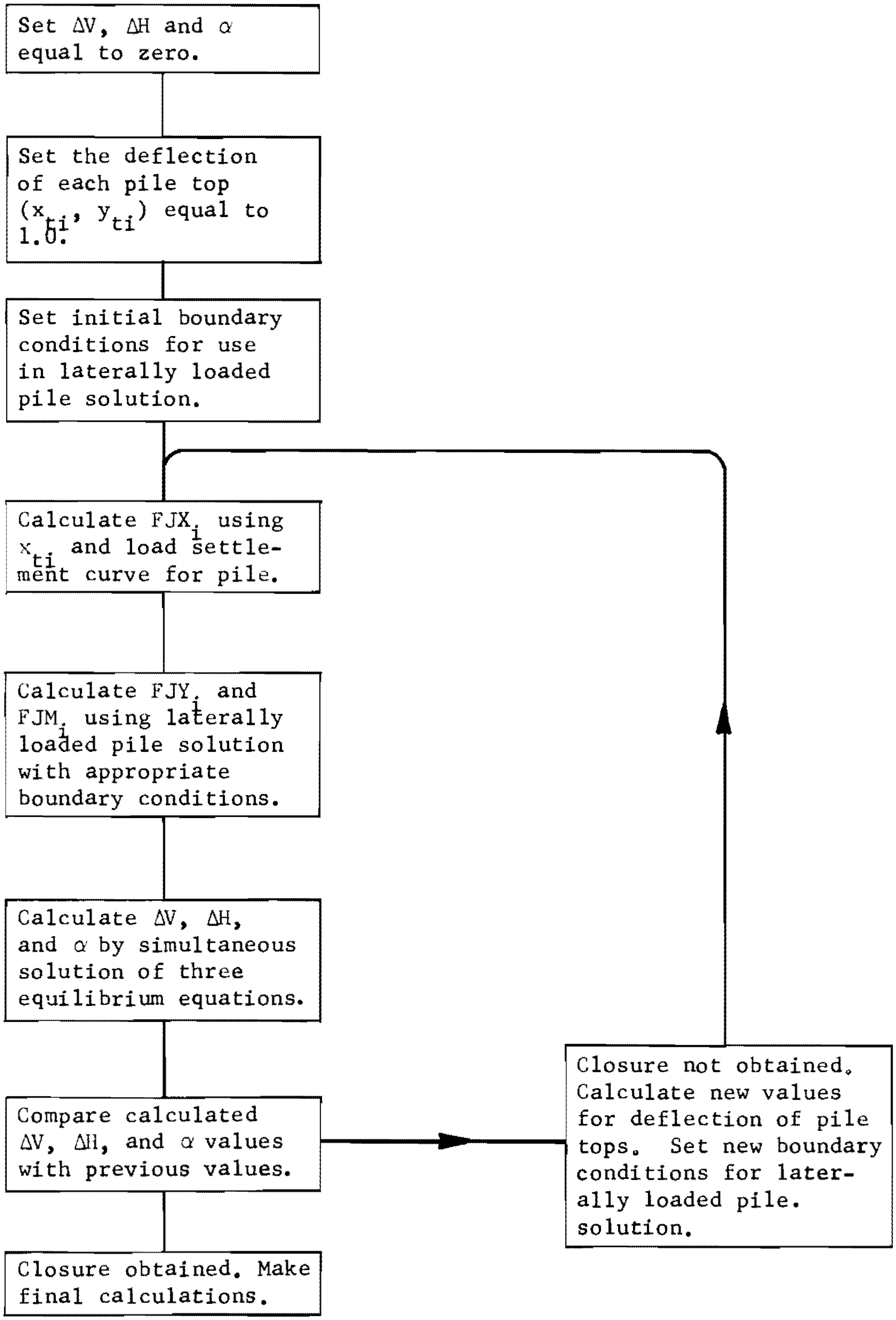


Fig. 22. Block diagram for iterative solution.

cedure is started. To start the procedure two assumptions are made. First the foundation movements (ΔV, ΔH, and α) are set equal to zero. Next the deflections of the pile heads (x_t and y_t) are set equal to one inch. These assumptions are made to get the iterative procedure started. Once the procedure is started it is continued until the equilibrium position for the structure is found.

The next step is to set the boundary conditions for the laterally loaded pile solution (SUBROUTINE COM62). For the initial iteration one boundary condition is that the lateral deflection of the pile tops is one inch. The second boundary condition will depend on the manner in which the pile is connected to the structure. The value of the second boundary condition will be set equal to zero for the initial iteration. For pin connections the second boundary condition used is the moment at the pile top. This means that if the pile is pinned to the structure the moment at the pile top is set equal to zero. For fixed connections this sets the slope at the pile top equal to zero, and for restrained connections the restraint at the top is set equal to zero.

With the initial assumptions and the initial boundary conditions, values for the spring moduli are calculated. FJX_i is calculated from the axial load-deflection curve using the axial deflection. To calculate FJY_i and FJM_i COM62 is entered with the initial boundary conditions. The deflected shape, the shear at the top, and the moment at the top are calculated, and thus the spring modulus values obtained.

With the spring moduli for each pile, the equilibrium equations are solved for the foundation movement. One cycle is complete when the pile head movements are calculated, using the components of the foundation movement obtained. The solution obtained is checked by comparing the calculated components of foundation movement with values from the previous iteration. The correct solution is obtained when the movements agree to within the allowable tolerance. The allowable tolerance is set by the input variable TOL. For ΔV and ΔH the iteration procedure is controlled by the input value of TOL. For control of α TOL is multiplied internally by 0.001. If closure is not obtained the procedure is repeated.

To start the second cycle, and each preceding cycle, the boundary conditions for the laterally loaded pile routine are set. One boundary condition is the shear at the top of the pile. This is found by multiplying FJY_i by the lateral deflection of the pile tops, as calculated from the foundation movements. The second boundary condition will depend on the manner in which the pile is connected to the foundation. For pinned connections the second boundary is that the top moment is zero. For fixed connections the slope at the top is set equal to the rotation of the structure. And, for restrained connections the second boundary condition is the restraint provided by the structure. The remainder of the procedure is the same as for the initial assumption. This procedure is continued until the correct foundation movement is obtained. When the correct movement is found a control is set and the forces and moment exerted by each pile on the structure are found. The deflected shape, moment distribution and soil reaction for each pile are also calculated. Examples of the output information for program BENT1 are presented in Appendix F.

CHAPTER VI

EXAMPLE PROBLEMS

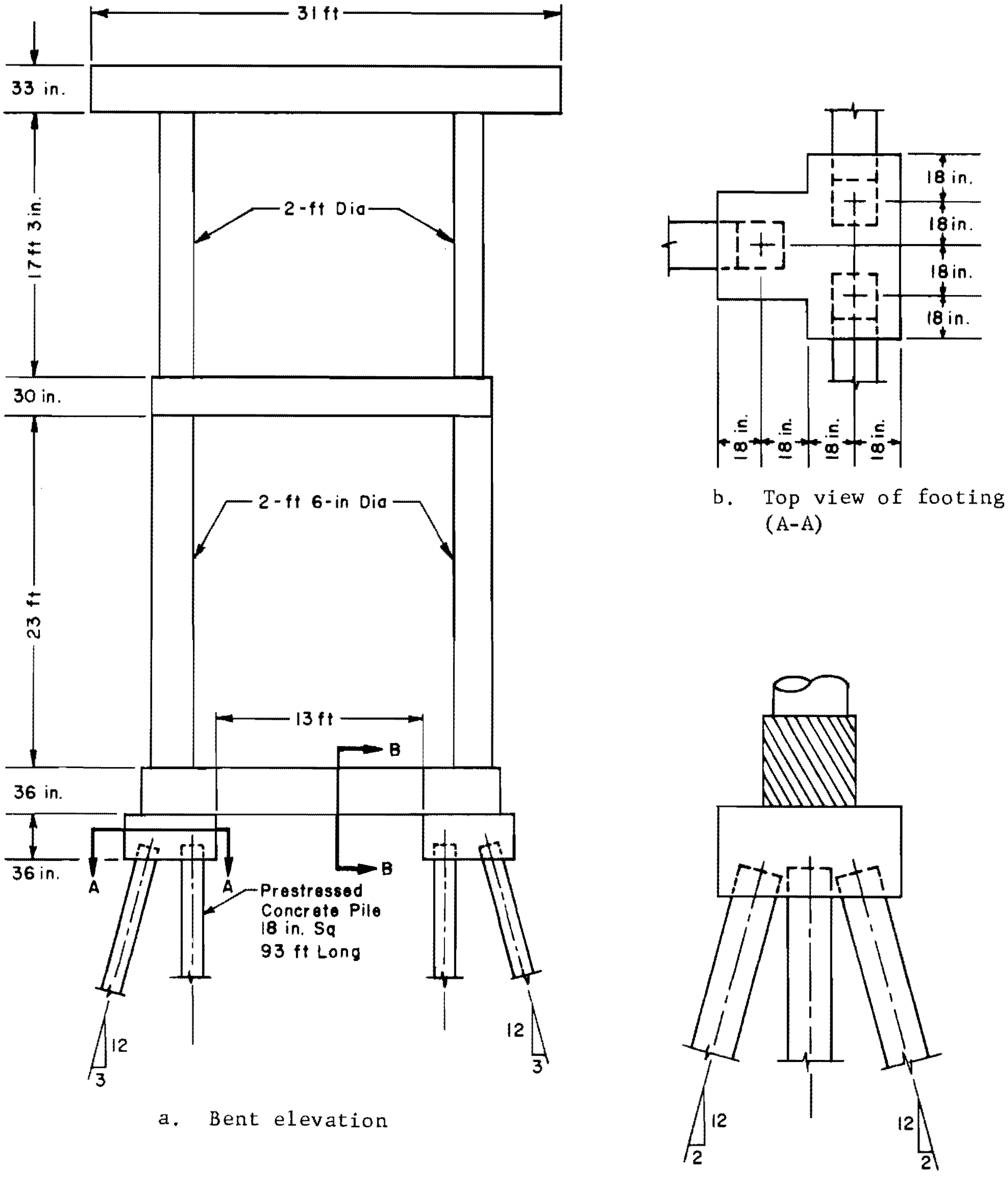
The two example problems presented in this chapter are associated with actual bents, used by the Texas Highway Department for supporting bridges on the Gulf Coast of Texas. The geometry of the bents, properties of the piles and soil, and the loads on the bents were obtained from highway department files.

GENERAL CHARACTERISTICS OF EXAMPLE PROBLEMS

The bents considered in the example problems are used in bridges located on the Gulf Coast of Texas. There are two basic reasons why bents of this type were selected for analysis by the proposed method. The first reason is that soil conditions in this area are consistently bad which makes piles necessary for bridge foundations. The second reason is that high lateral loads are common. These are due primarily to wind and wave action. During hurricanes the lateral loads may be quite high. The use of long piles and high lateral loads makes the proposed method of analysis seem very attractive for these bents.

COPANO BAY CAUSEWAY

The first example considered will be one of the bents used in the Copano Bay Causeway. The bridge is located in Aransas County on State Highway 35, between Port Lavaca and Rockport. The bridge is 920 ft in length and provides 50 ft vertical clearance at the center of the span. The roadway is supported by precast-prestressed concrete girders. The bent caps, columns, and footings are reinforced concrete. The bent heights vary from 20 to 50 ft. The bent analyzed is shown in Fig. 23. The piles used are battered in 4 directions to



a. Bent elevation

b. Top view of footing (A-A)

c. Side view of footing (B-B)

Fig. 23. Copano Bay Causeway bent.

resist horizontal forces perpendicular and parallel to the roadway. Only the case where the horizontal load is perpendicular to roadway will be considered. For this case the two interior piles in each footing, which are battered parallel to the roadway, will be treated as vertical piles. The bottom tie beam is considered to provide sufficient rigidity so that the assumption that the pile heads remain in the same plane after movement is valid.

The geometry necessary for describing the foundation for the computer solution is shown in Fig. 24 and Table I. The coordinate system and the resulting forces on the bent are also shown in this figure. The piles are 18 in. square prestressed concrete piles. They have an effective flexural rigidity of 4.374×10^{10} lb-in.^{2} (assuming a modulus of elasticity for concrete of 5×10^6 psi) and a length of 93 ft.

A pile similar to the ones used in the bent was driven near the site of the bent. A load test was performed on this pile. The load settlement curve obtained and used in the computer solution is shown in Fig. 25.

The piles are driven through what is classified as muck or very soft clay, to bearing on a dense sand or firm sandy clay. The location of the stiffer strata is variable and so the length of piles and length of embedment in the stiffer strata will be variable. For this analysis the piles are assumed to be 93 ft in length with an embedment length of 83 ft.

For generation of p-y curves the soil is treated as a clay. That is, the soil is treated as a frictionless material with the shear strength composed entirely of cohesion. Some thin sand layers are encountered but their effect is considered insignificant. The tip of the pile may also be buried to several feet in a sand or sandy clay, but the effect on the lateral behavior will be insignificant and will be ignored.

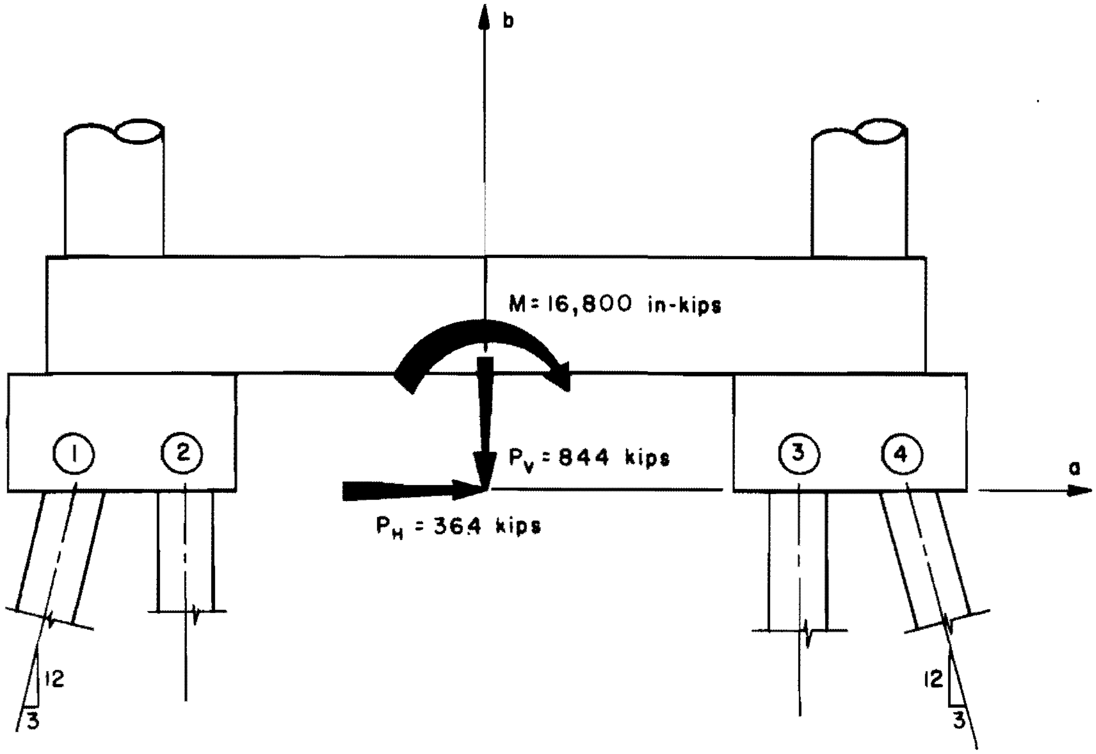


Fig. 24. Foundation representation - Copano Bay.

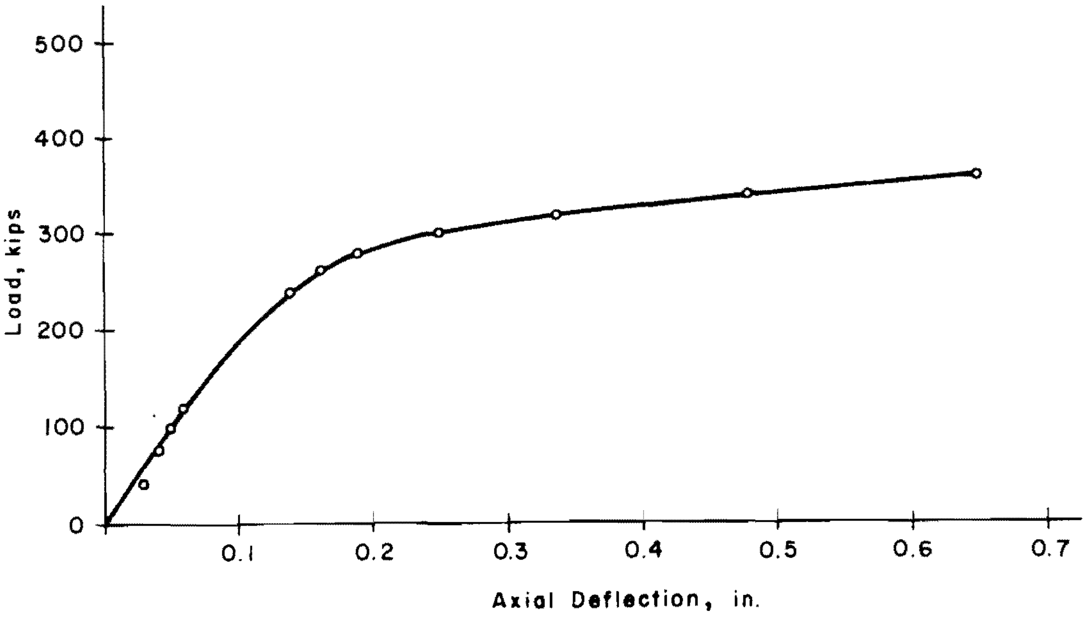


Fig. 25. Load deflection curve - Copano Bay.

TABLE I. PILE LOCATION INFORMATION - COPANO BAY

Pile Location	a Coordinate (in.)	b Coordinate (in.)	No. Piles at Location	Batter (radians)
1	-126	0	1	-0.244
2	- 90	0	2	0.0
3	+ 90	0	2	0.0
4	+126	0	1	+0.244

TABLE II. PILE LOADS AND MOVEMENT - COPANO BAY

Pile Location	Axial Load per Pile (kips)	Lateral Load per Pile (kips)	Moment per Pile (in.-kips)	Axial Movement (in.)	Lateral Movement (in.)
1	78.7	1.7	-253.3	0.0397	0.1134
2	133.4	1.5	-218.9	0.0689	0.1004
3	156.5	1.5	-218.8	0.0843	0.1004
4	193.6	1.1	-155.2	0.1091	0.0763

After considering boring logs from the vicinity of the bent and after a review of triaxial data, a variation of cohesion with depth was assumed and used for predicting lateral pile-soil interaction. This assumed distribution of cohesion along the pile length is shown in Fig. 26. The depth given is the distance from the soil surface. The top of the piles are located at the water surface which is 10 ft above the soil surface. The scourline is assumed to be 5 ft below the soil surface. The saturated unit weight of the soil is taken as 92 pcf, and the consistency is soft.

A solution was obtained for this problem by using the program BENT1 which was described in Chapter V. The movement of the bent is described by the following movements of the origin of the a-b coordinate system.

$$\Delta V = 7.664 \times 10^{-2} \text{ in.}$$

$$\Delta H = 1.004 \times 10^{-1} \text{ in.}$$

$$\alpha = 8.536 \times 10^{-5} \text{ radians}$$

The loads transferred to each pile and the movements of each pile top are tabulated in Table II. The forces and movements at the pile tops are related to the x-y coordinate system set up for each pile.

The deflection of the a-b coordinate system defines the equilibrium position for the structure. When the foundation is in this position the piles exert on the foundation the given forces and moments which satisfy the three equilibrium equations. A complete listing of the coded input and output are presented in Appendices E and F.

If the movement of the structure and the loads carried by each pile are considered, it would appear that the design is conservative. This is probably true, but it should be pointed out that factors such as settlement caused by consolidation and cyclic loading have not been considered.

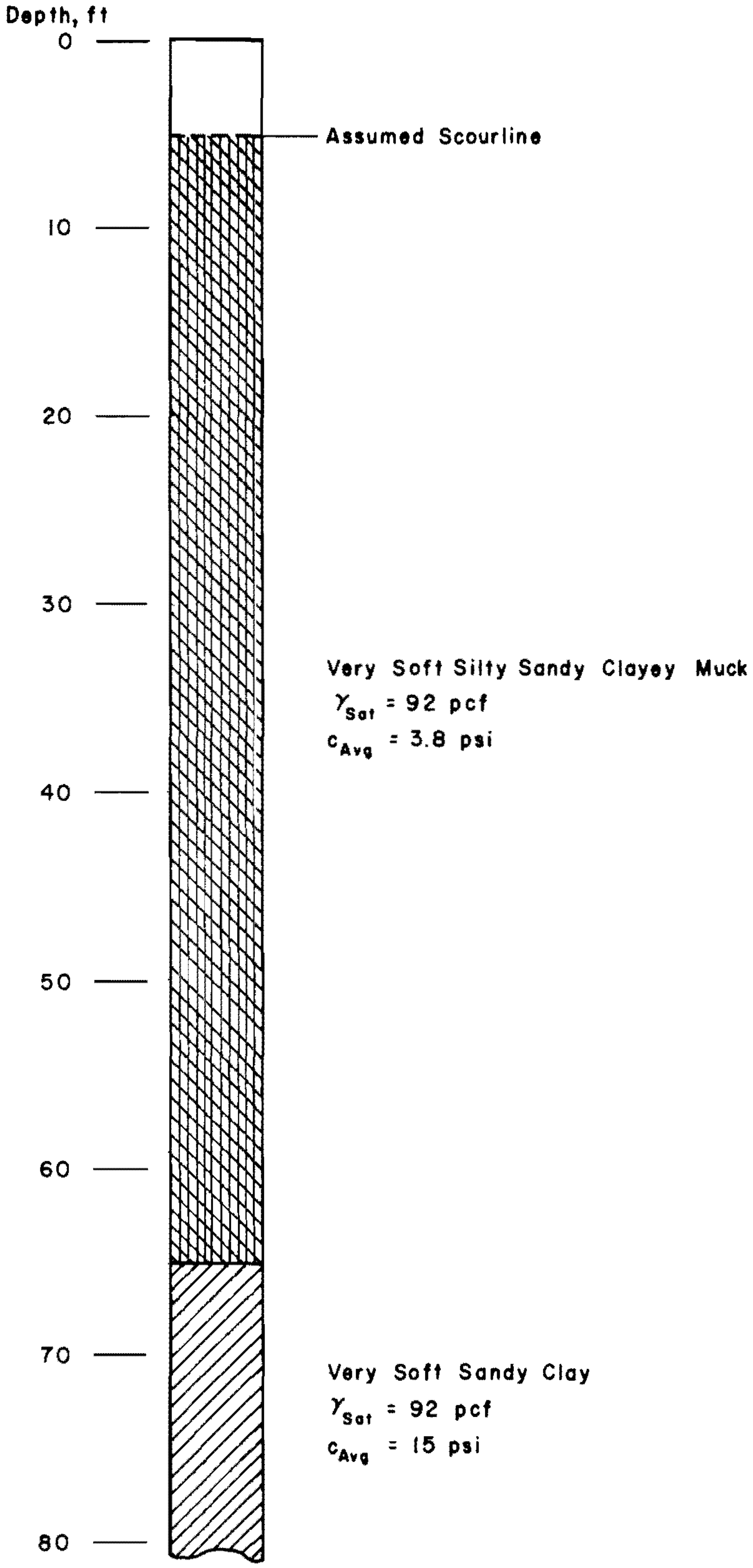


Fig. 26. Soil properties for generation of p-y curves.

HOUSTON SHIP CHANNEL

The second example considered will be one of the bents used in a bridge across the Houston Ship Channel. The bridge is located in Harris County on Interstate Highway 610. Details of the bent analyzed are shown in Fig. 27. The bent is reinforced concrete and is supported by 142 - 18 in. square precast-prestressed concrete piles. The piles in this example are battered parallel to the roadway to resist horizontal loads from the superstructure. It is assumed that the 7 ft thick pile cap provides sufficient rigidity so that the assumption of plane movement is valid.

The geometry necessary for describing the foundation for the computer solution is shown in Fig. 28 and Table III. The coordinate system and the loads on the structure are also shown in the figure. The piles have an effective flexural rigidity of 4.374×10^{10} lb-in.^{2} (assuming a modulus of elasticity of concrete of 5×10^6 psi) and a length of 44 ft.

No axial load-deflection curves obtained from load tests are available for the piles used in the bent. Because of this it was necessary to estimate the axial behavior of the piles. The ultimate bearing capacity of the piles was estimated as 650 kips in compression and 600 kips in tension. The ultimate deflection is estimated as 0.5 in. The load-deflection relationship is assumed to be linear resulting in a curve as shown in Fig. 29.

The properties of the soil used for predicting the lateral pile-soil interaction were obtained from highway department borings. The properties used for generation of p-y curves are shown in Fig. 30. It should be pointed out that the profile shown is a simplification of the actual profile. The top 13 ft of soil, defined as very dense sandy silt, will be treated as a sand when p-y curves are generated. That is, it will be treated as a cohesionless material. The bottom 31 ft, defined as very stiff silty clay, will be

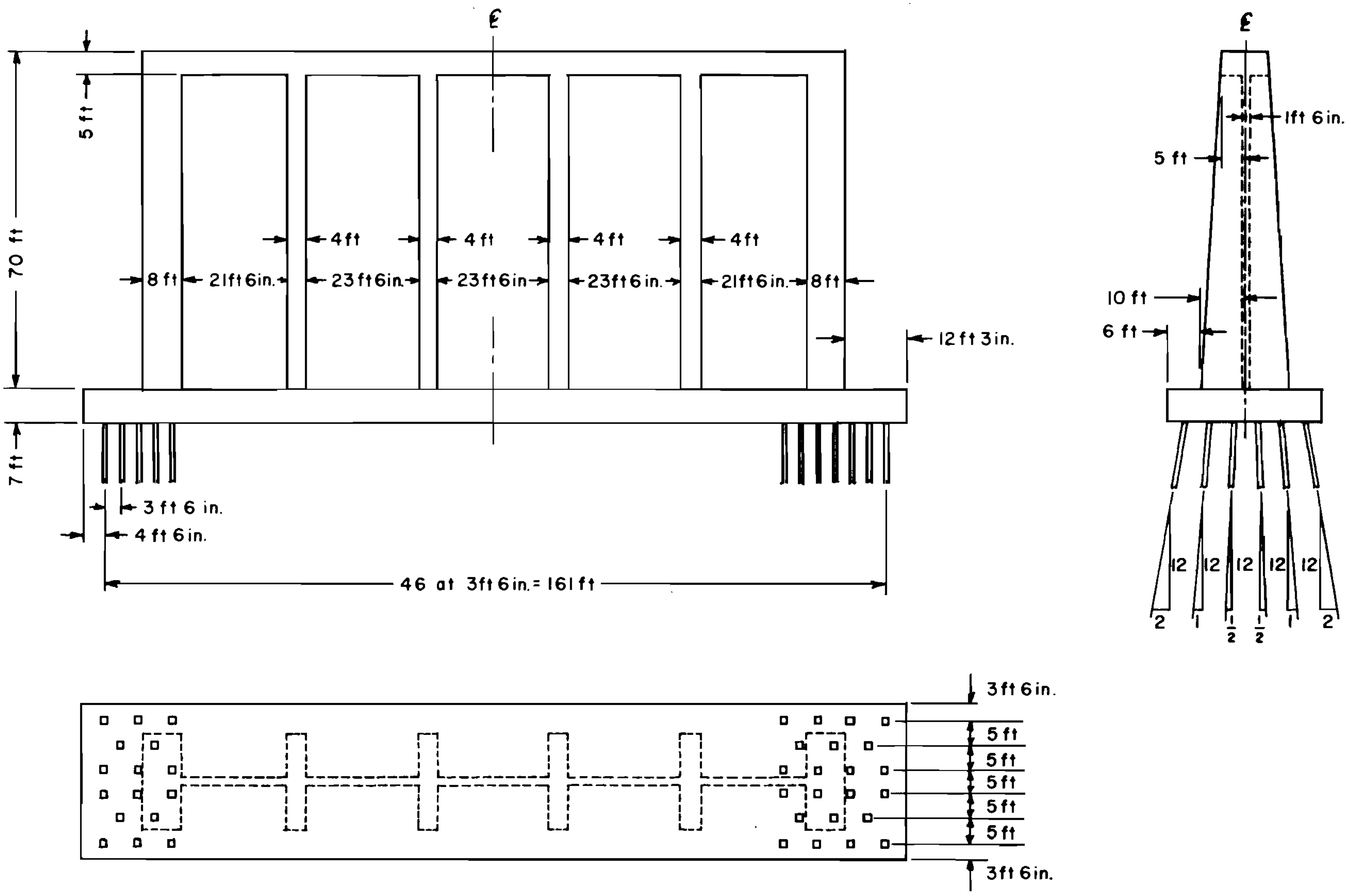


Fig. 27. Houston Ship Channel bent.

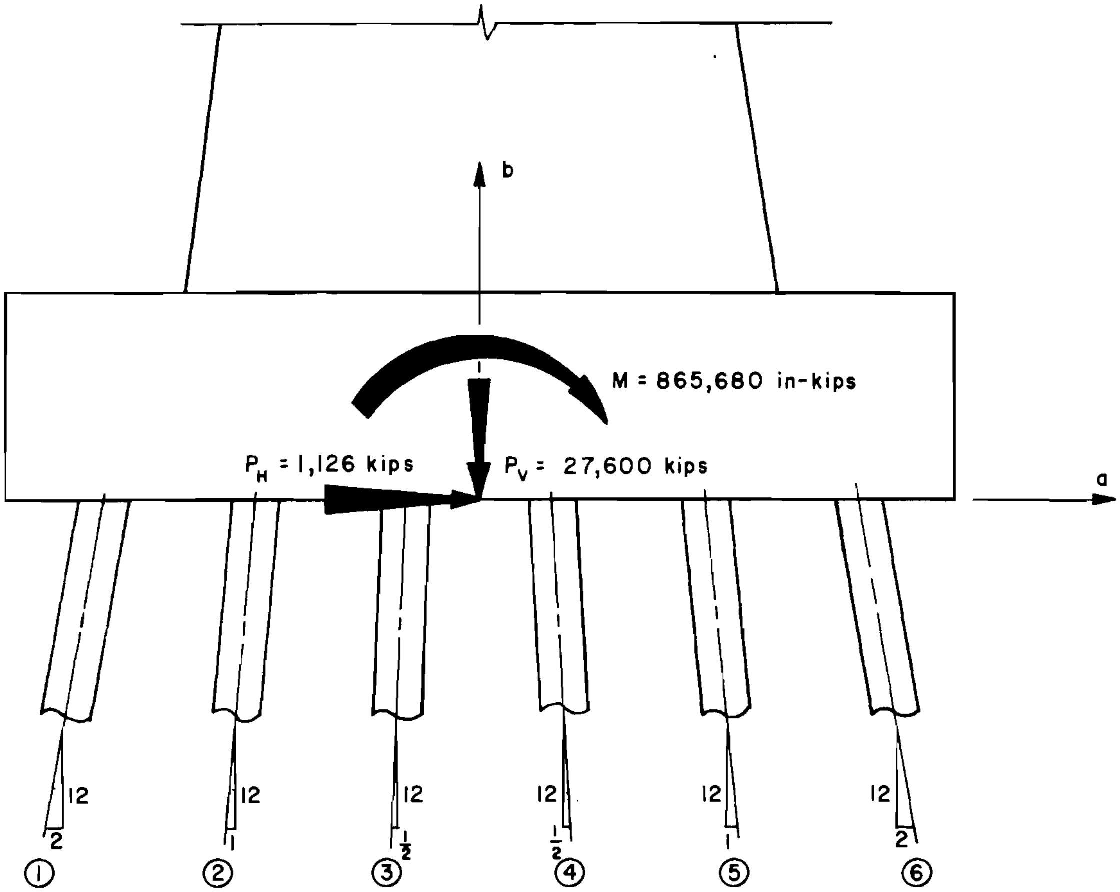


Fig. 28. Foundation representation - Ship Channel.

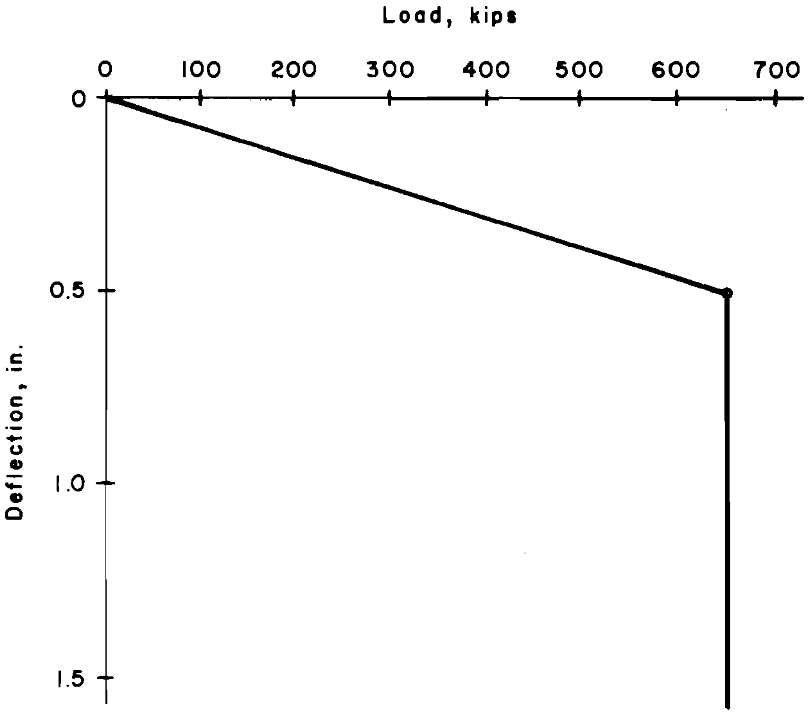


Fig. 29. Estimated axial load deformation curve - Ship Channel.

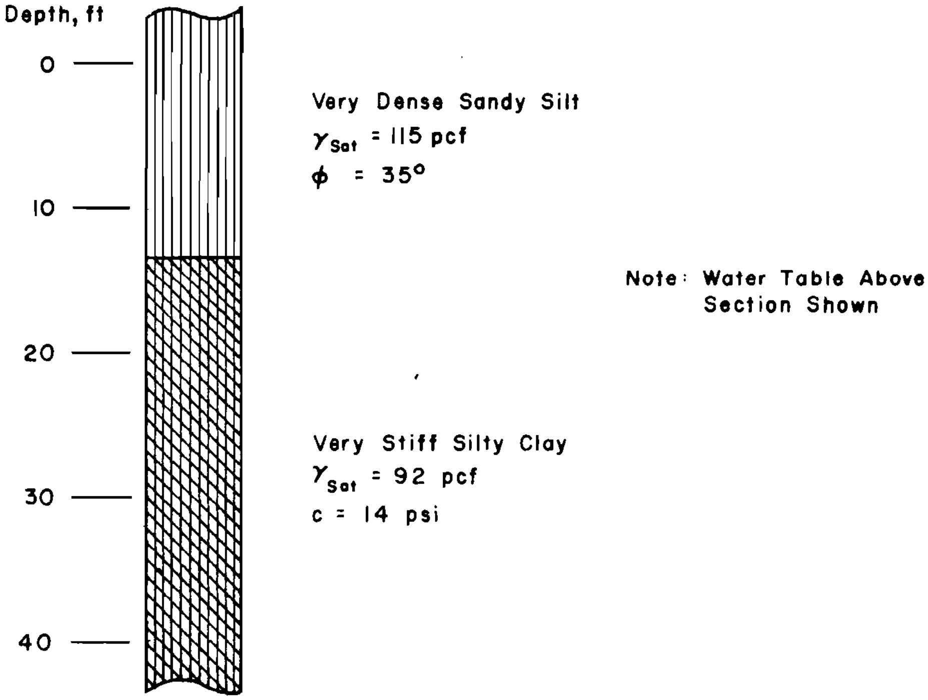


Fig. 30. Soil properties for p-y curves - Ship Channel.

TABLE III. PILE LOCATION INFORMATION - SHIP CHANNEL

Pile Location	a Coordinate (in.)	b Coordinate (in.)	No. Piles at Location	Batter (radians)
1	-150	0	24	-0.166
2	- 90	0	23	-0.083
3	- 30	0	24	-0.042
4	30	0	24	0.042
5	90	0	23	0.083
6	150	0	24	0.166

TABLE IV. PILE LOADS AND MOVEMENTS - SHIP CHANNEL

Pile Location	Axial Load per Pile (kips)	Lateral Load per Pile (kips)	Moment per Pile (in.-kips)	Axial Movement (in.)	Lateral Movement (in.)
1	106.3	3.3	-46.0	0.0818	0.0474
2	143.6	2.5	0.4	0.1104	0.0425
3	178.3	2.0	32.8	0.1372	0.0390
4	214.5	0.3	122.1	0.1650	0.0263
5	248.3	0.2	83.8	0.1910	0.0174
6	281.5	0.0	-15.2	0.2165	-0.0026

treated as a clay. That is, it will be treated as a frictionless material. Depths given are measured from the top of the pile. From the given soil properties, p-y curves are generated. These are shown in Appendix F.

A solution was obtained for the Ship Channel problem by using the program BENT1. The movement of the bent, when loaded, is described by the following movements of the origin of the a-b coordinate system.

$$\Delta V = 1.512 \times 10^{-1} \text{ in.}$$

$$\Delta H = 3.321 \times 10^{-2} \text{ in.}$$

$$\alpha = 4.183 \times 10^{-4} \text{ radians.}$$

The loads transferred to each pile and the movements of each pile top are tabulated in Table IV. The forces and movements at the pile tops are related to the x-y coordinate systems set up for each pile. A complete set of coded input is given in Appendix E. The output is shown in Appendix F.

The small deflections and loads obtained for the piles would tend to indicate that the design is conservative. This is probably true, and is to be expected. But, it should be pointed out that a number of factors, such as consolidation and cyclic loading have not been considered. It must also be pointed out that the load deflection curve used is only a rough approximation. The value used for ultimate load is probably fairly reliable, but the deflection at which the load stops increasing is only an educated guess. Because of this a linear variation of load with movement was considered to provide sufficient refinement. The effect of this will be reflected in the loads and deflections obtained for the piles. The loads obtained will probably be fairly accurate but the accuracy of the movements obtained will depend on the accuracy of the value which was assumed for the deflection at which the load stops increasing.

CHAPTER VII

SUMMARY AND CONCLUSIONS

The UT method, for analyzing two-dimensional pile supported foundations, is the most complete method which has been considered in this study. The improvements over the other methods considered are summarized in the conclusions to Chapter II. The major improvements are the ability to consider the nonlinear load-deflection relationships for the piles and the ability to consider any type of pile-to-foundation connection.

The consideration of only two-dimensional configurations and the assumption that the pile heads remain in the same plane before and after loading are not serious limitations of the method. For a great many practical engineering problems these two requirements are approximated to a degree so that the results obtained provide useful information.

The method assumes that the piles in the bent behave as individually loaded piles. The problem with the method is not in the method of computation but rather with predicting the behavior of the individual piles in the bent. This problem may be considered in two parts.

In the first consideration, methods must be available for predicting the lateral and axial behavior of the individual piles. This subject is discussed in Chapter IV and it was concluded that a load test is the only proven way to determine axial behavior, and that the method presented for predicting lateral interaction is based on theoretical considerations and a limited amount of field data.

The second consideration is the spacing of the piles. The spacing of the piles at which the behavior of one pile is influenced by the surrounding piles is not well defined. There is no general agreement as to the minimum spacing at which this influence is felt or the magnitude of the influence. This factor must be considered if the solutions obtained are to be meaningful, since it has been assumed that the piles act independently.

Other factors which should be considered are the effect of axial load on lateral behavior and lateral load on axial behavior. An attempt has been made to include the effect of axial load on lateral behavior by considering the effect of axial load on the deflected shape of the pile. The axial load is considered to be constant over the entire length of the pile. This is an incorrect assumption since some load is removed by skin friction. It is felt that no further refinement is justified because of the inability to accurately predict the variation with depth and because the effect on the accuracy is considered insignificant. No provision is made for considering the efffect of lateral load on axial behavior. Any adjustment would have to be made through the axial load-deflection curve.

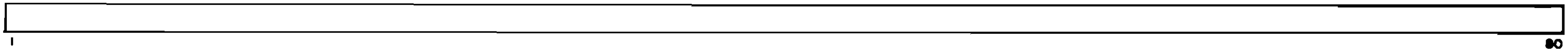
The UT method is a rational approach to a complicated problem. It can provide information which will aid the designer and it will aid in understanding the mechanics of a pile supported foundation. This information should be used only after careful consideration is given to the assumptions involved in providing input information. Research will eliminate many of the uncertainties involved, but for the present it must be remembered that the accuracy of the solutions obtained depend on the accuracy of the input information.

APPENDIX A

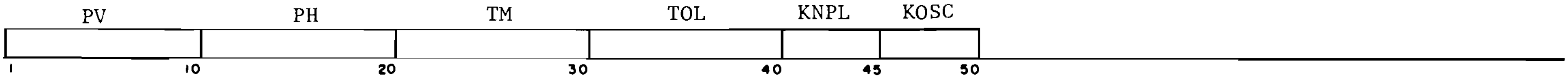
GUIDE FOR DATA INPUT

BENT1 GUIDE FOR DATA INPUT -- Card forms

IDENTIFICATION OF PROBLEM (1 alphanumeric card per problem)



FOUNDATION LOAD AND CONTROL DATA (1 card per problem)



PV - VERTICAL LOAD ON FOUNDATION

PH - HORIZONTAL LOAD ON FOUNDATION

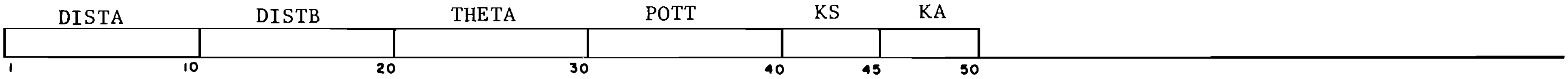
TM - MOMENT ON FOUNDATION

TOL - ITERATION TOLERANCE

KNPL - NUMBER OF PILE LOCATIONS

KOSC - SWITCH TO CONTROL OSCILLATING SOLUTION
(Set equal to 1 if solution oscillates. Set equal to 0 for normal use.)

CONTROL DATA FOR PILE LOCATIONS (1 card per pile location)



DISTA - HORIZONTAL COORDINATE OF PILE TOP

DISTB - VERTICAL COORDINATE OF PILE TOP

THETA - PILE BATTER

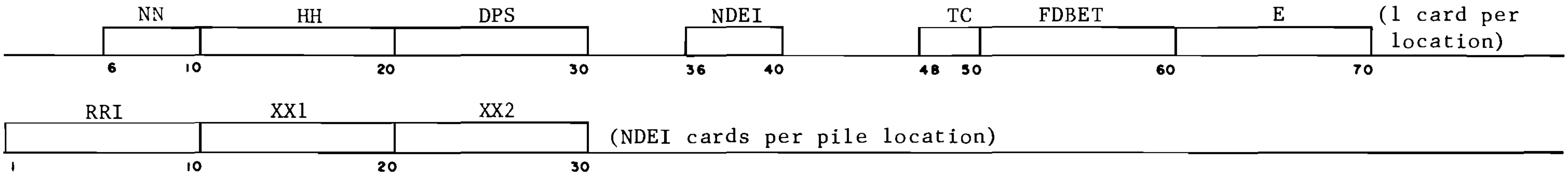
POTT - NUMBER OF PILES AT A LOCATION

KS - IDENTIFIER TO RELATE PILE TO p-y CURVE

KA - IDENTIFIER TO RELATE PILE TO AXIAL LOAD SETTLEMENT CURVE

Note: KS and KA are necessary for selecting the correct set of p-y curves and axial load settlement curve for a pile. This option is made available because for some problems all piles may not behave alike. These two variables correspond to IDPY and IDEN which are input with p-y and load settlement data.

CONTROL DATA FOR PILES (KNPL sets per problem)



NN - NUMBER OF INCREMENTS

HH - INCREMENT LENGTH

DPS - DISTANCE FROM PILE TOP TO SOIL SURFACE

NDEI - NUMBER OF DIFFERENT EI VALUES IN PILE

TC - ALPHANUMERIC DESIGNATION FOR TOP CONNECTION OF PILE
(FIX - Fixed connection, PIN - Pinned connection, RES - Restrained connection)

FDBET - ROTATIONAL RESTRAINT (Not necessary unless TC = RES)

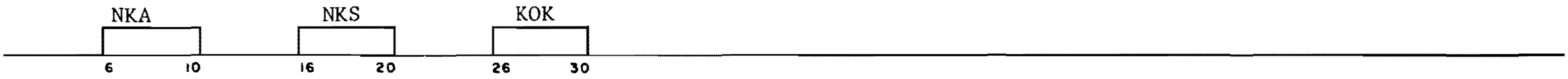
E - PILE DIAMETER OR WIDTH

RRI - FLEXURAL STIFFNESS (EI) OF A SECTION

XX1 - DISTANCE FROM PILE TOP TO TOP OF SECTION

XX2 - DISTANCE FROM PILE TOP TO BOTTOM OF SECTION

CONTROL DATA FOR SOIL PROPERTIES (1 card per problem)

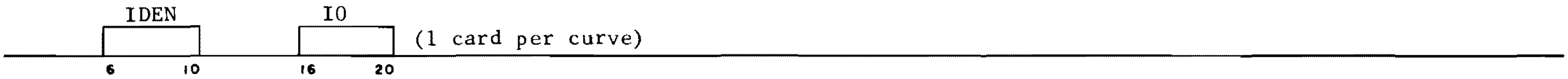


NKA - NUMBER OF LOAD SETTLEMENT CURVES

NKS - NUMBER OF SETS OF p-y CURVES

KOK - SWITCH FOR INPUT OF p-y CURVES (KOK = 0 p-y curves input, KOK = 1 p-y curves generated)

CONTROL AND DATA FOR AXIAL LOAD SETTLEMENT CURVES (NKA sets per problem)



(1 card per curve)

(IO cards per curve)

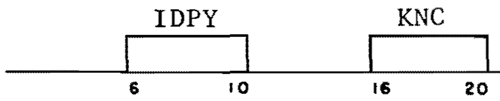
IDEN - IDENTIFIER FOR AXIAL LOAD SETTLEMENT CURVE (Corresponds to KA)

IO - NUMBER OF POINTS ON CURVE

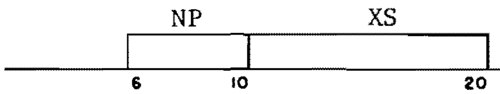
ZZZ - AXIAL SETTLEMENT

SSS - AXIAL LOAD

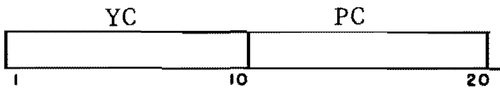
CONTROL DATA for p-y CURVES (Necessary only if KOK = 0, NKS sets per problem)



(1 card per set of curves)



(1 card per curve)



(NP cards per curve)

IDPY - IDENTIFIER FOR SET OF p-y CURVES (Corresponds to KS)

KNC - NUMBER OF CURVES IN SET

NP - NUMBER OF POINTS ON CURVE

XS - DISTANCE FROM GROUND LINE TO CURVE

YC - DEFLECTION ON CURVE

PC - SOIL REACTION ON CURVE

Note: The following cards are necessary only if p-y curves are to be generated, i.e., KOK = 1. This permits direct generation of p-y curves from soil and pile properties. More than one soil condition is permitted (NSOILP) and more than one type pile is permitted (NPISP). The various soil conditions and types of piles may be combined to produce appropriate sets of p-y curves.

NSOILP	
6 – 10	(1 card per problem)

NSOILP - NUMBER OF SOIL PROFILES

CONTROL DATA FOR SOIL PROFILES (1 set per soil profile)

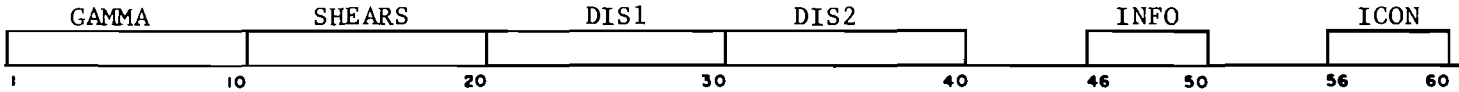
NSTYPE	
6 – 10	(1 card per profile)

TSOIL	
7 – 10	(1 card per stratum)

GAMMA	PHI	DIS1	DIS2	KDENSE	
1 – 10	11 – 20	21 – 30	31 – 40	47 – 50	(1 card per stratum)

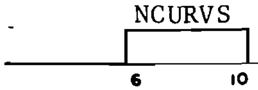
Note: If TSOIL = SAND the following cards in set are omitted for stratum.

If TSOIL = CLAY the above card is omitted and all or part of following cards in set are necessary.

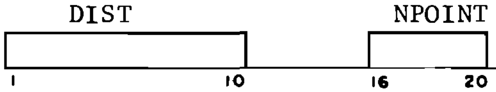


(1 card per stratum)

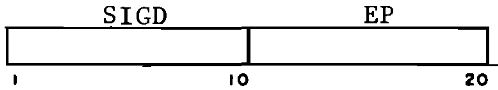
Note: If INFO = 0 following cards in set are omitted. If INFO = 1 they are necessary.



(1 card per stratum)



(1 card per stress strain curve)



(NPOINT cards per curve)

NSTYPE - NUMBER OF STRATA IN PROFILE

TSOIL - ALPHANUMERIC DESIGNATION OF TYPE SOIL IN STRATUM (SAND OR CLAY)

GAMMA - UNIT WEIGHT OF SOIL

PHI - ANGLE OF INTERNAL FRICTION FOR SAND

DIS1 - DISTANCE FROM GROUND LINE TO TOP OF STRATUM

DIS2 - DISTANCE FROM GROUND LINE TO BOTTOM OF STRATUM

KDENSE - ALPHANUMERIC DESIGNATION FOR RELATIVE DENSITY OF SAND (DENSE, MEDUM OR LOOSE)

SHEARS - COHESION OF CLAY

INFO - CONTROL FOR INPUT OF STRESS-STRAIN CURVES (INFO = 1 curves input)

ICON - ALPHANUMERIC DESIGNATION FOR CONSISTENCY OF CLAY (SOFT or STIF)

NCURVS - NUMBER OF CURVES PER STRATUM

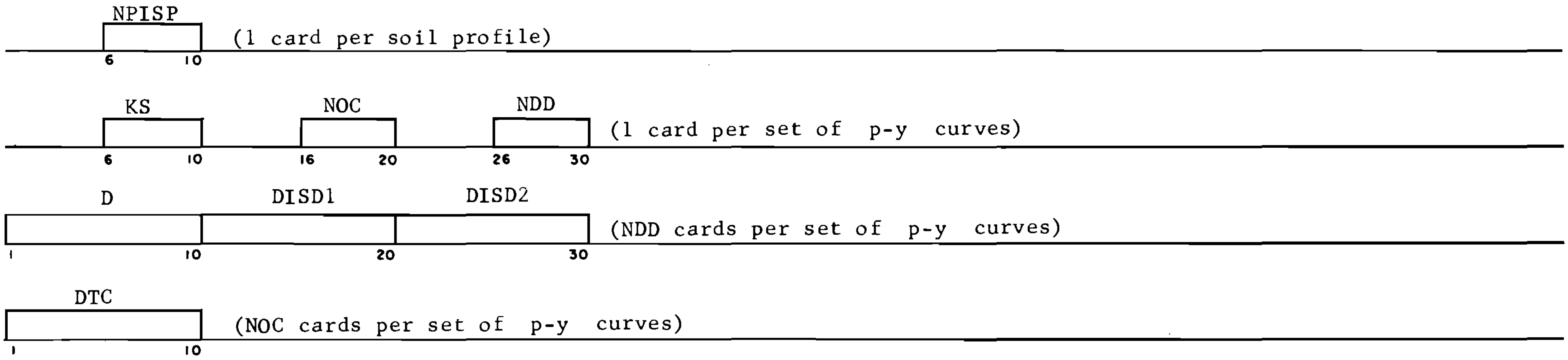
DIST - DISTANCE FROM GROUNDLINE TO CURVE

NPOINT - NUMBER OF POINTS ON CURVE

SIGD - DEVIATOR STRESS

EP - AXIAL STRAIN

PILE PARAMETERS AND CONTROL DATA FOR GENERATION OF p-y CURVES



NPISP - NUMBER OF DIFFERENT PILES IN A SOIL PROFILE.

KS - IDENTIFIER FOR SET OF p-y CURVES

NOC - NUMBER OF CURVES IN SET

NDD - NUMBER OF DIFFERENT DIAMETERS USED FOR p-y CURVES

D - PILE DIAMETER

DISD1 - DISTANCE FROM TOP OF PILE TO TOP OF SECTION

DISD2 - DISTANCE FROM TOP OF PILE TO BOTTOM OF SECTION

DTC - DISTANCE FROM TOP OF PILE TO p-y CURVE

STOP CARDS (2 blank cards at end of run)

1 80

1 80

GENERAL PROGRAM NOTES

All input values in units of pounds, inches and radians.
All 5-space words are right justified integers, unless specified as on alphanumeric word.
All 10-space words are floating-point decimal numbers.
Data cards must be stacked in proper sequence.
Where a group of cards are referred to as a set, the cards in the set must be stacked in the sequence shown. Sets are then stacked.
Several problems may be run by stacking data for additional problems behind first problem.
Two blank cards behind last problem stops the program.

LIMITS ON SIZE OF INPUT VARIABLES

KNPL - Maximum number of pile locations is 20.

NN - Maximum number of increments into which pile may be divided is 100.

NDEI - Maximum of 5 different EI values per pile.

NKA - Maximum of 5 different load settlement curves per problem.

NKS - Maximum of 5 different sets of p-y curves per problem.

IO - Maximum number of points on load settlement curve is 25.

KNC - Maximum of 20 p-y curves per set.

NP - Maximum of 25 points per p-y curve.

NSTYPE - Maximum of 10 strata per soil profile.

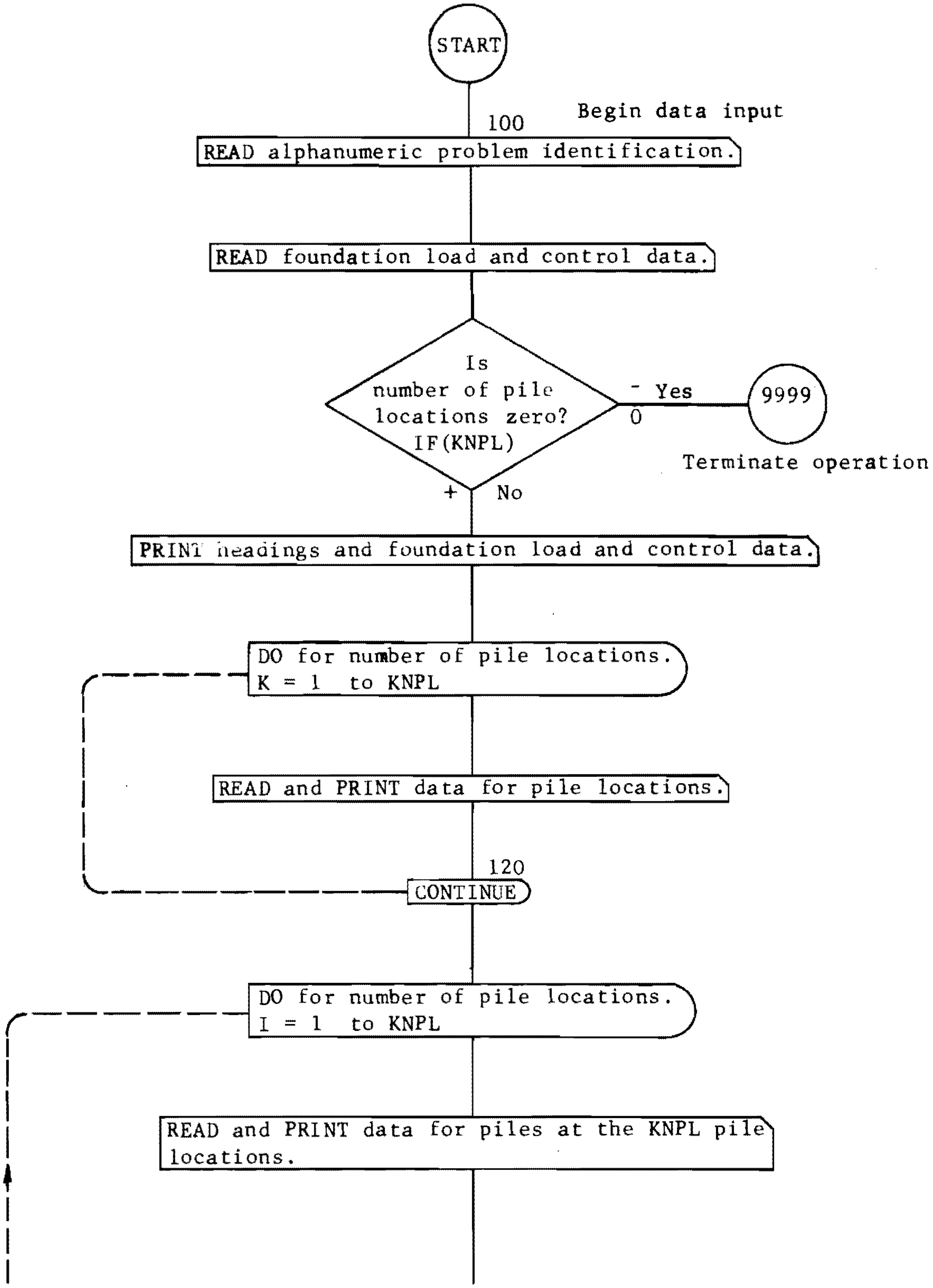
NCURVS - Maximum of 10 stress-strain curves per strata.

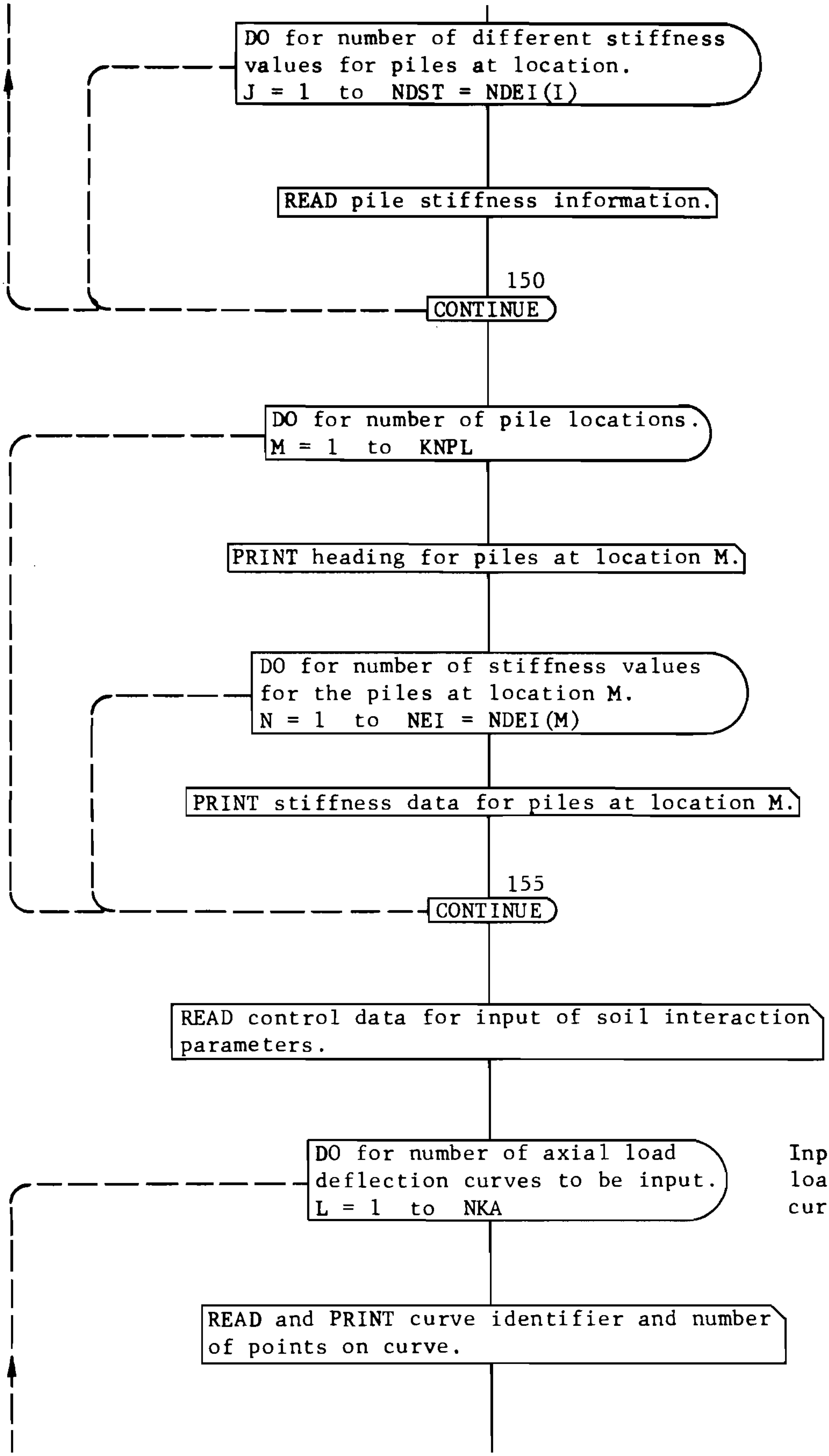
NPOINT - Maximum of 10 points per stress-strain curve.

APPENDIX B

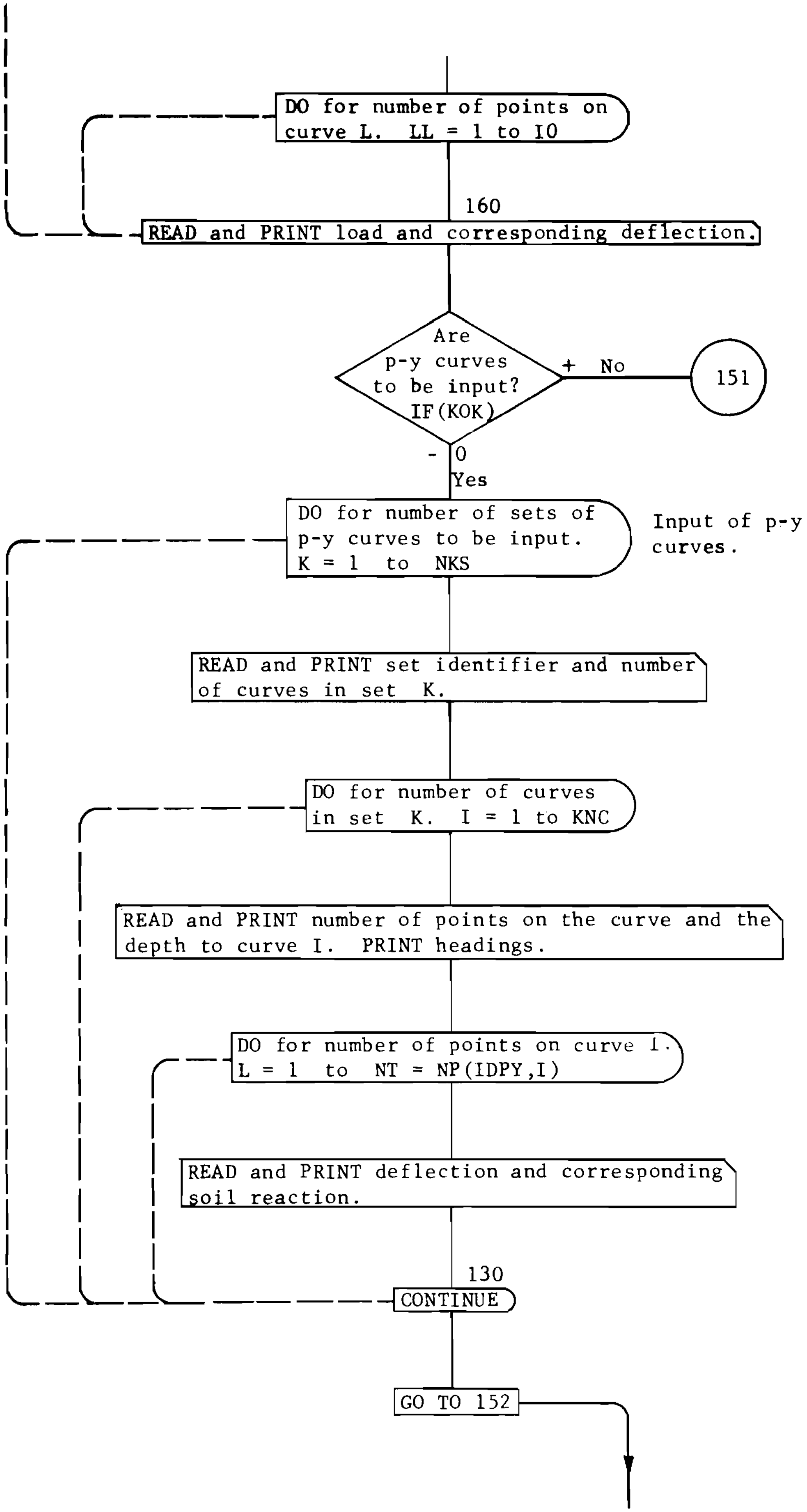
FLOW CHART FOR BENT1

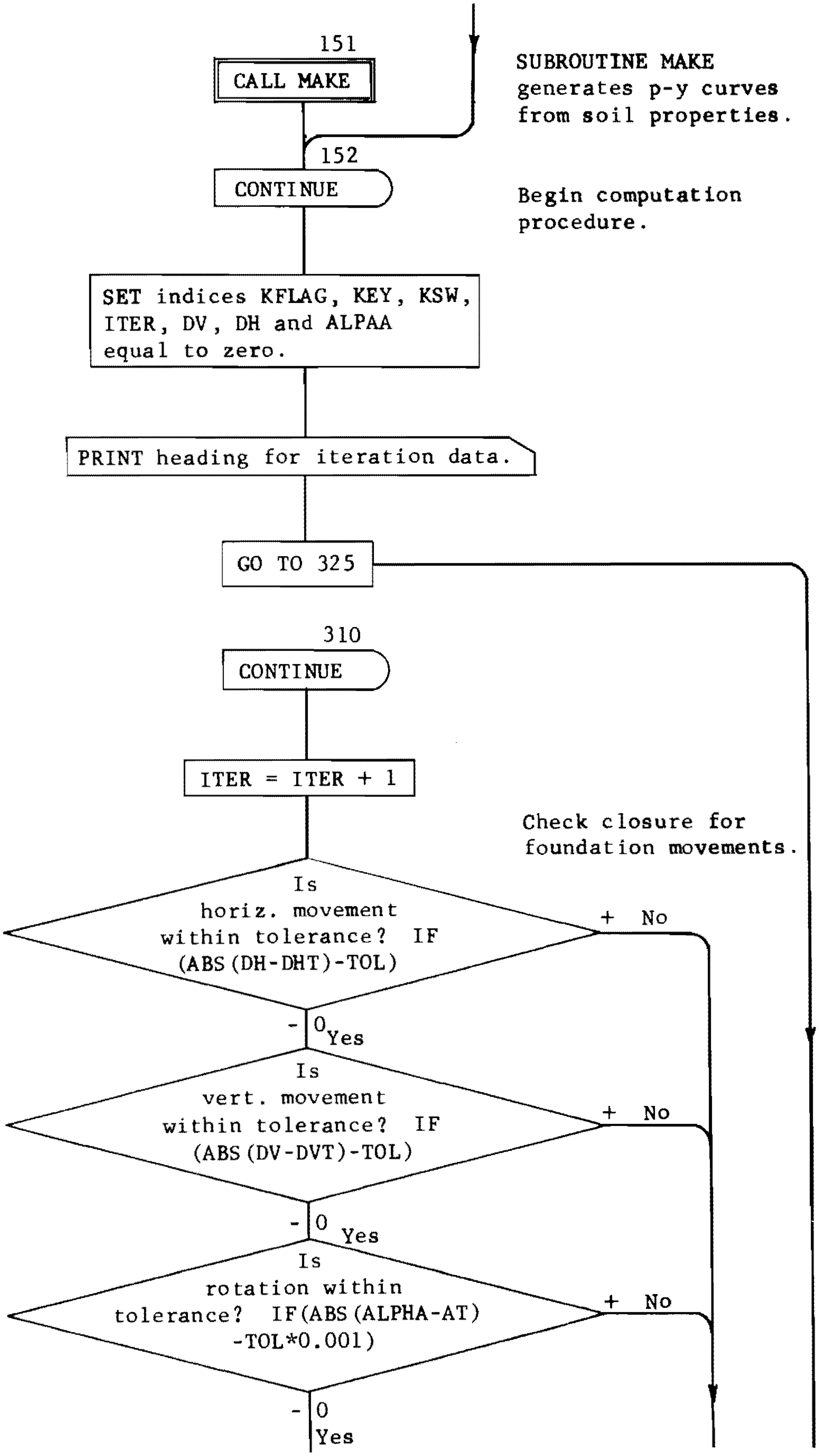
BENT 1


START
100
Begin data input
READ alphanumeric problem identification.
READ foundation load and control data.
Is number of pile locations zero? IF(KNPL)
- Yes
0
9999
Terminate operation
+
No
PRINT headings and foundation load and control data.
DO for number of pile locations.
K = 1 to KNPL
READ and PRINT data for pile locations.
120
CONTINUE
DO for number of pile locations.
I = 1 to KNPL
READ and PRINT data for piles at the KNPL pile locations.



Input of axial load deflection curves.

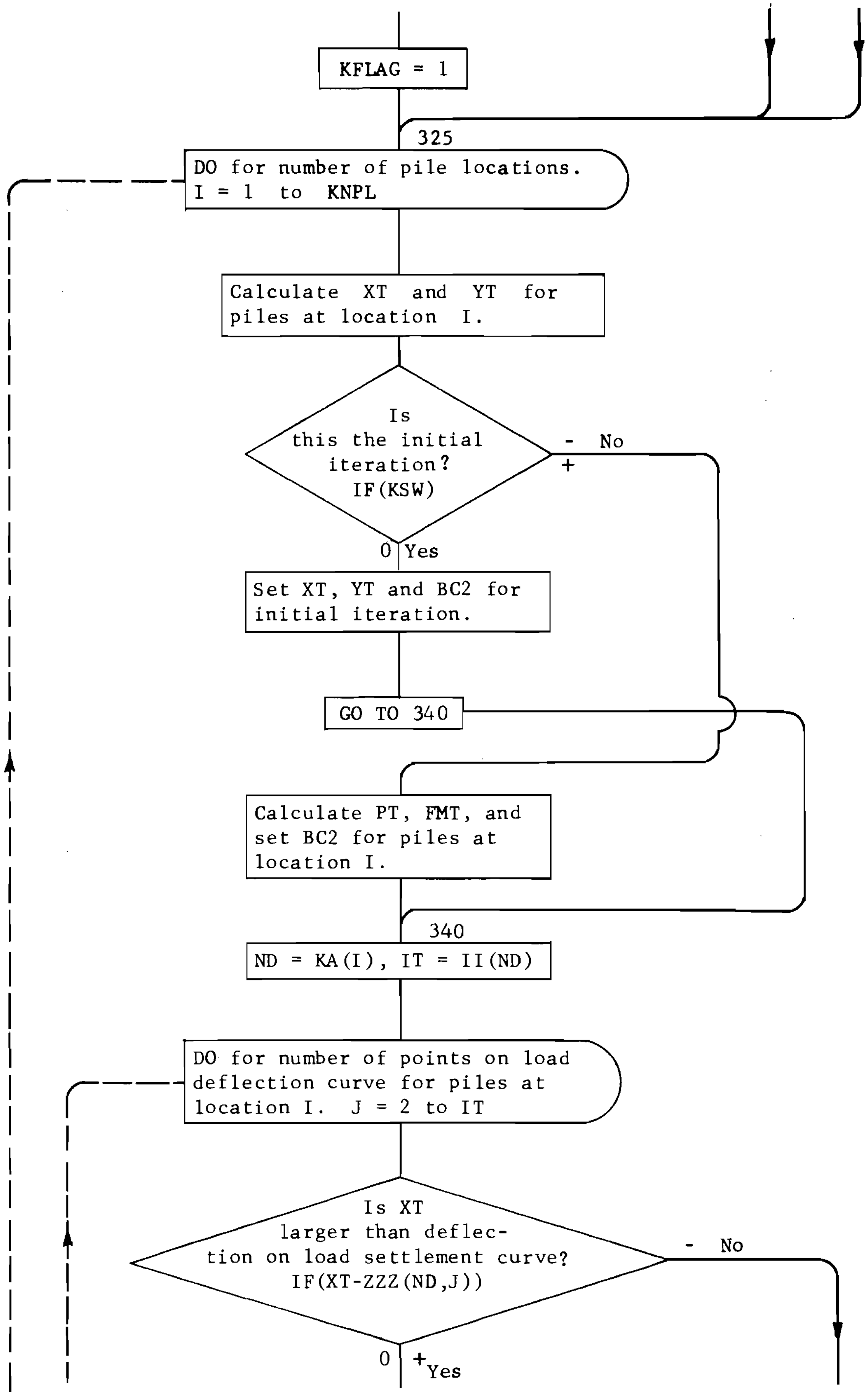

DO for number of points on curve L. LL = 1 to 10
160
READ and PRINT load and corresponding deflection.
Are p-y curves to be input? IF(KOK)
+ No
151
- 0 Yes
DO for number of sets of p-y curves to be input. K = 1 to NKS
Input of p-y curves.
READ and PRINT set identifier and number of curves in set K.
DO for number of curves in set K. I = 1 to KNC
READ and PRINT number of points on the curve and the depth to curve I. PRINT headings.
DO for number of points on curve I. L = 1 to NT = NP(IDPY,I)
READ and PRINT deflection and corresponding soil reaction.
130
CONTINUE
GO TO 152

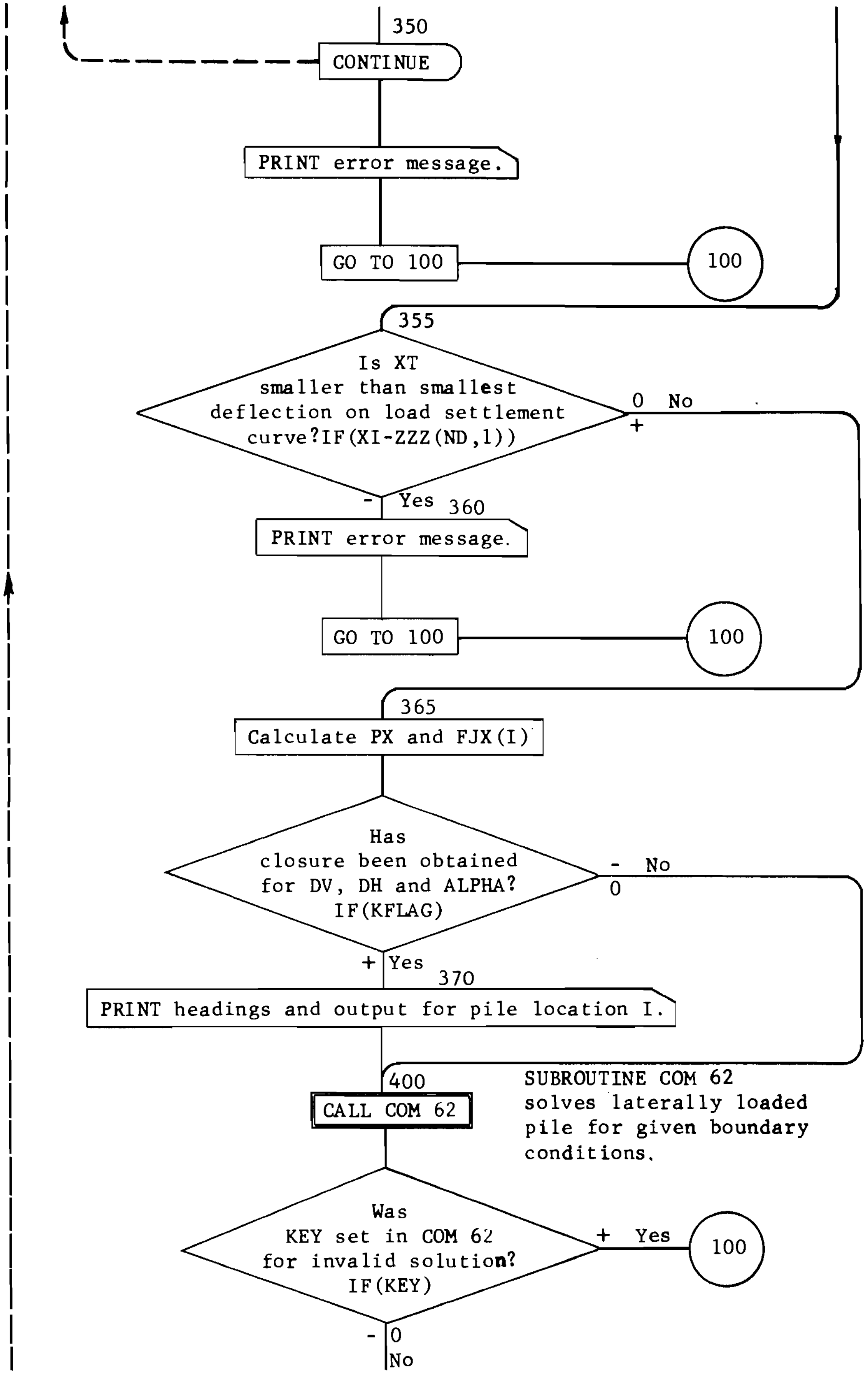


SUBROUTINE MAKE generates p-y curves from soil properties.

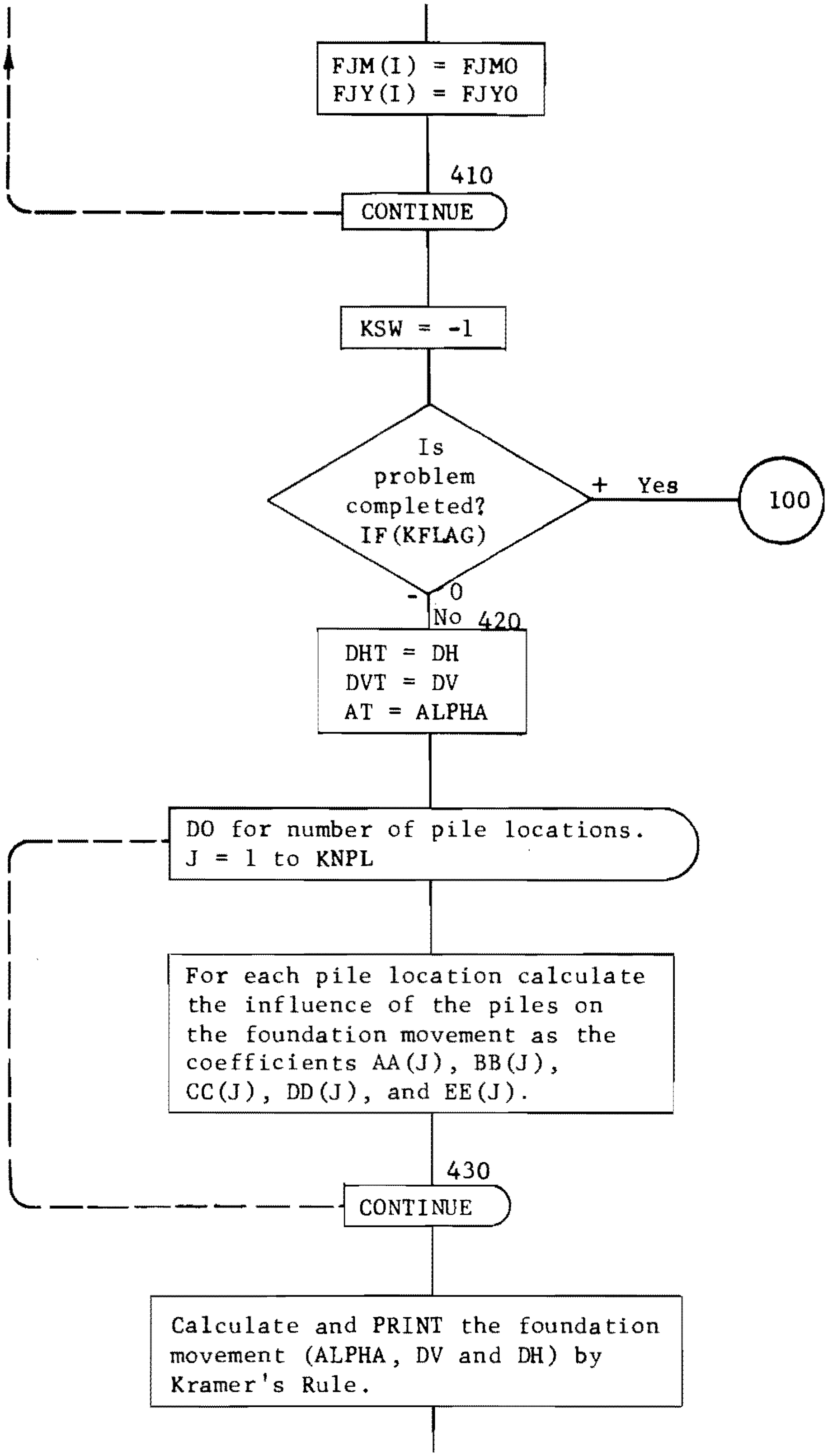
Begin computation procedure.

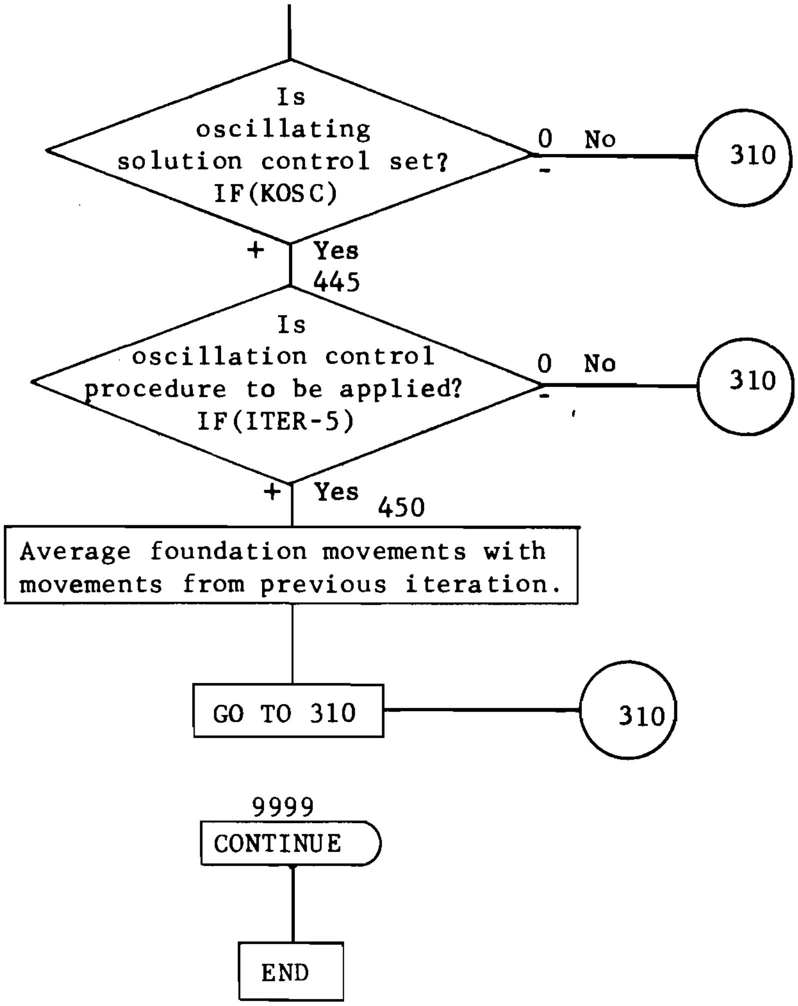
Check closure for foundation movements.


KFLAG = 1
325
DO for number of pile locations. I = 1 to KNPL
Calculate XT and YT for piles at location I.
Is this the initial iteration? IF(KSW)
- No
+
0 Yes
Set XT, YT and BC2 for initial iteration.
GO TO 340
Calculate PT, FMT, and set BC2 for piles at location I.
340
ND = KA(I), IT = II(ND)
DO for number of points on load deflection curve for piles at location I. J = 2 to IT
Is XT larger than deflection on load settlement curve? IF(XT-ZZZ(ND,J))
- No
0 +Yes



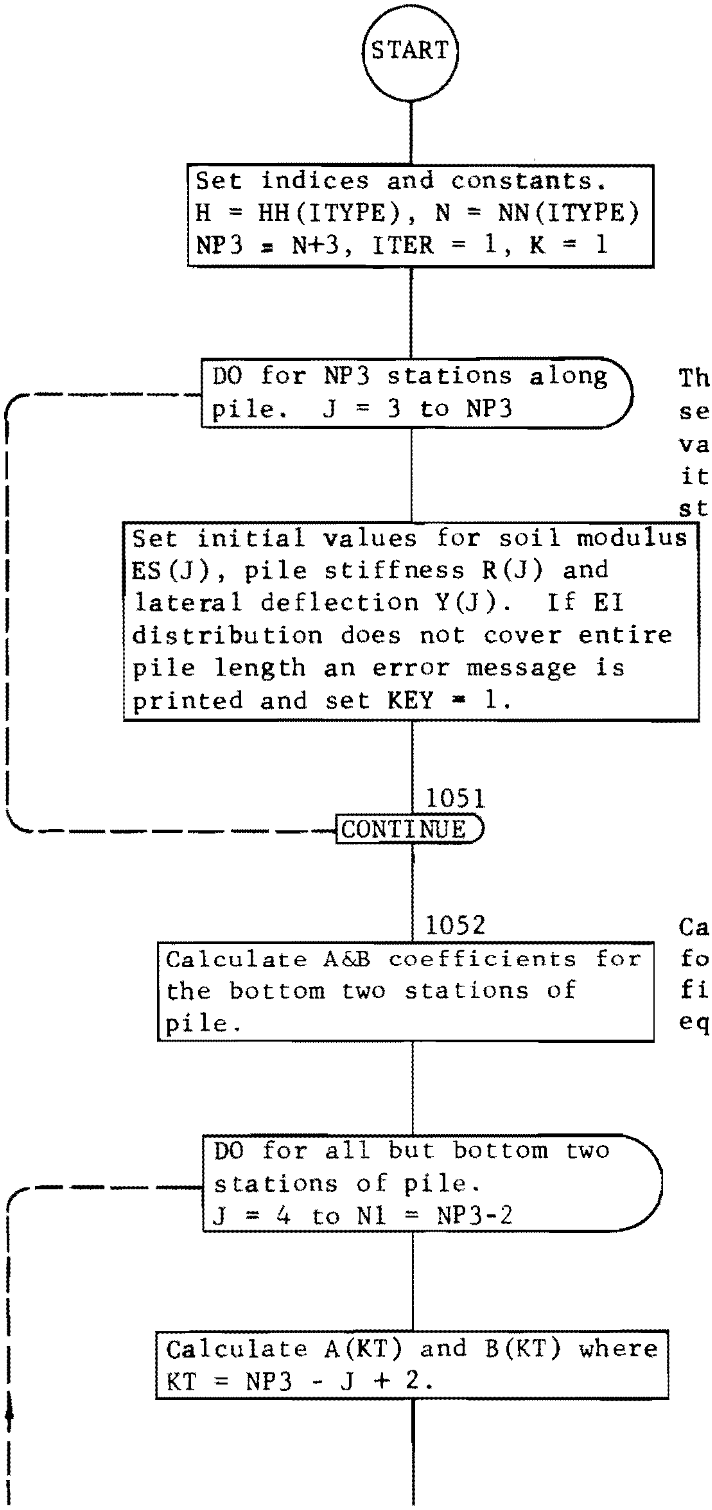
SUBROUTINE COM 62 solves laterally loaded pile for given boundary conditions.


FJM(I) = FJMO
FJY(I) = FJYO
410
CONTINUE
KSW = -1
Is problem completed? IF(KFLAG)
+
Yes
100
-
0
No
420
DHT = DH
DVT = DV
AT = ALPHA
DO for number of pile locations. J = 1 to KNPL
For each pile location calculate the influence of the piles on the foundation movement as the coefficients AA(J), BB(J), CC(J), DD(J), and EE(J).
430
CONTINUE
Calculate and PRINT the foundation movement (ALPHA, DV and DH) by Kramer's Rule.


Is oscillating solution control set? IF(KOSC)
0 No
-
310
+ Yes
445
Is oscillation control procedure to be applied? IF(ITER-5)
0 No
-
310
+ Yes
450
Average foundation movements with movements from previous iteration.
GO TO 310
310
9999
CONTINUE
END

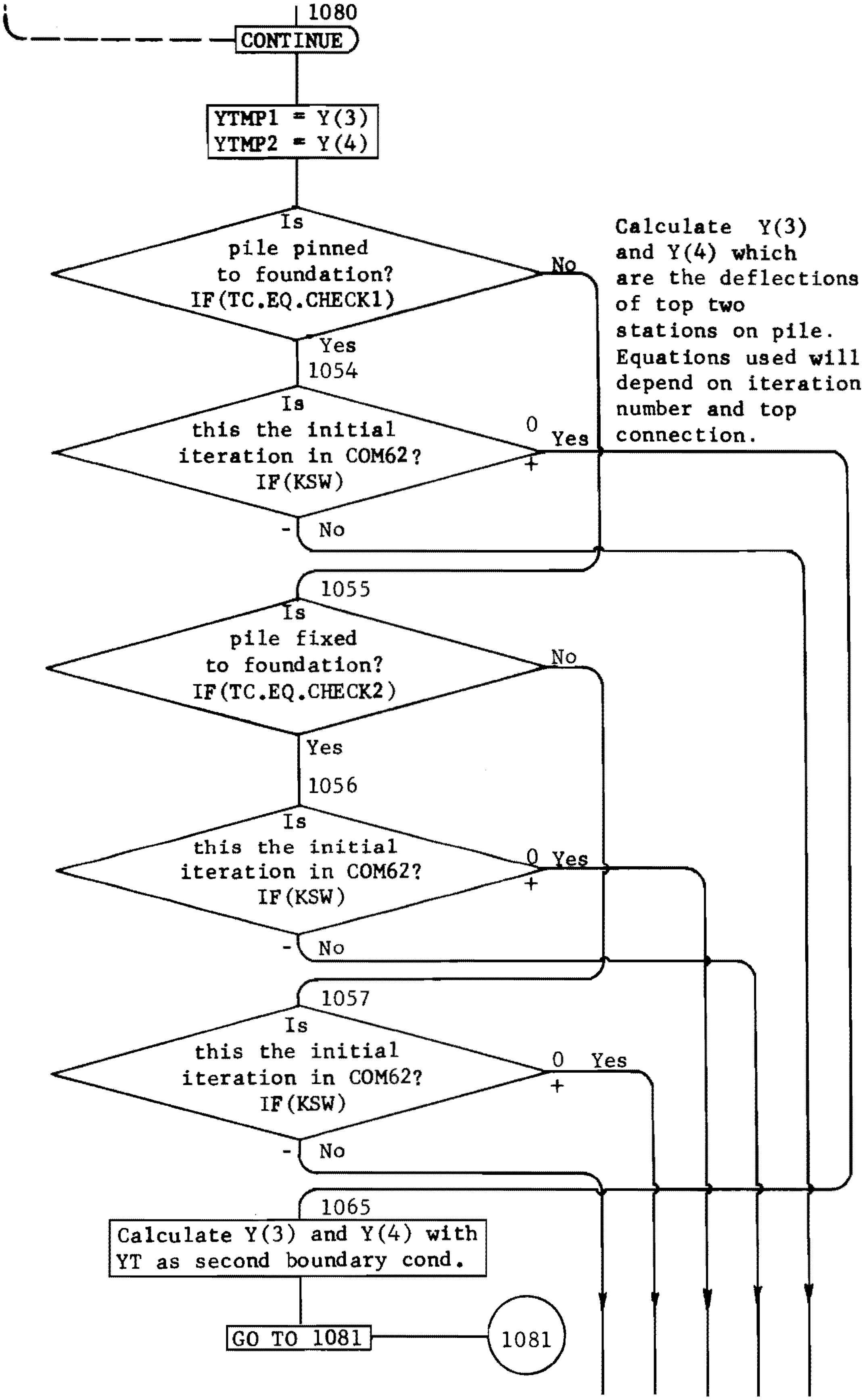
SUBROUTINE COM62.

This subroutine solves laterally loaded pile for given boundary conditions.

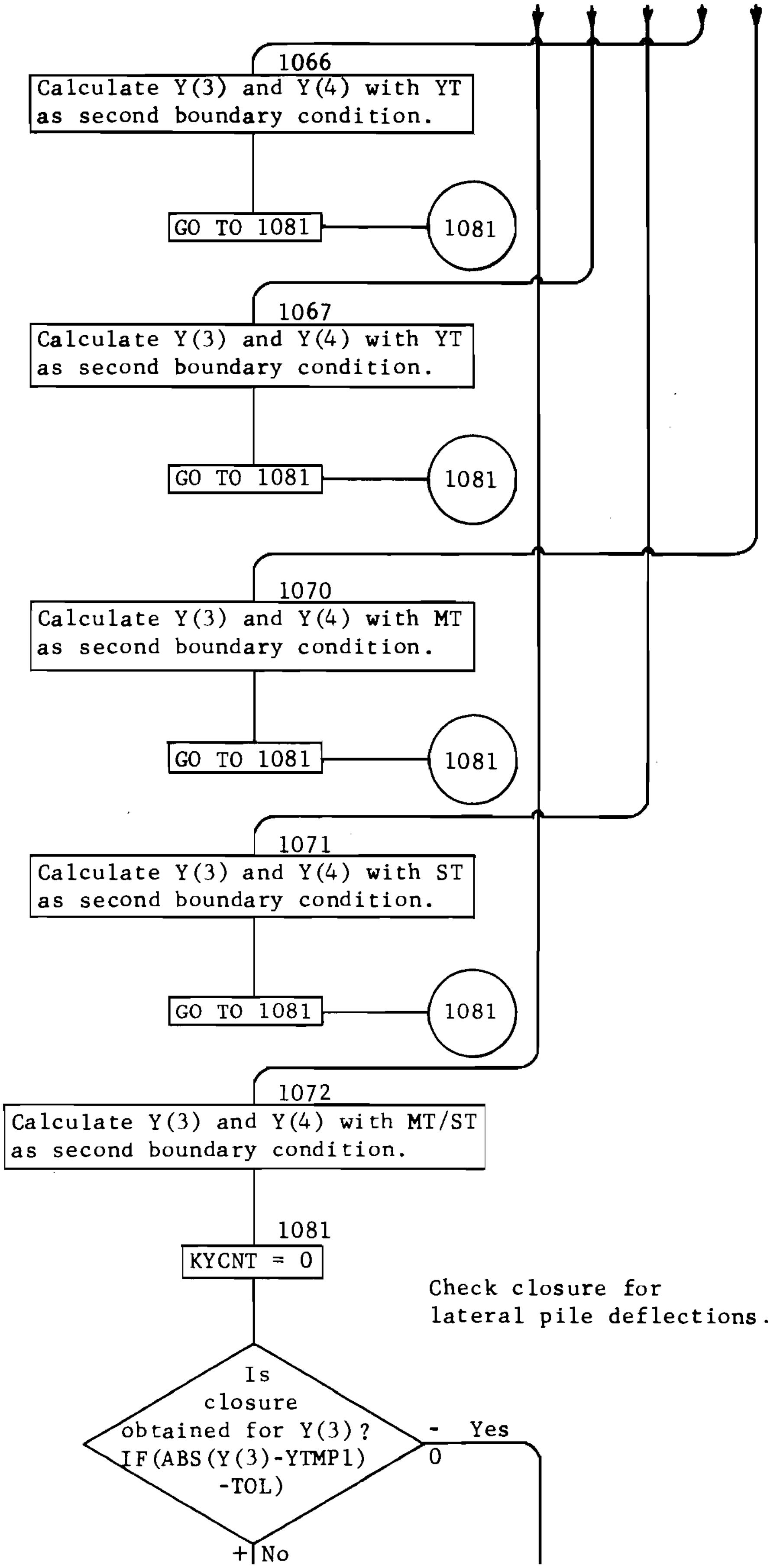


This DO loop sets initial values to get iteration procedure started.

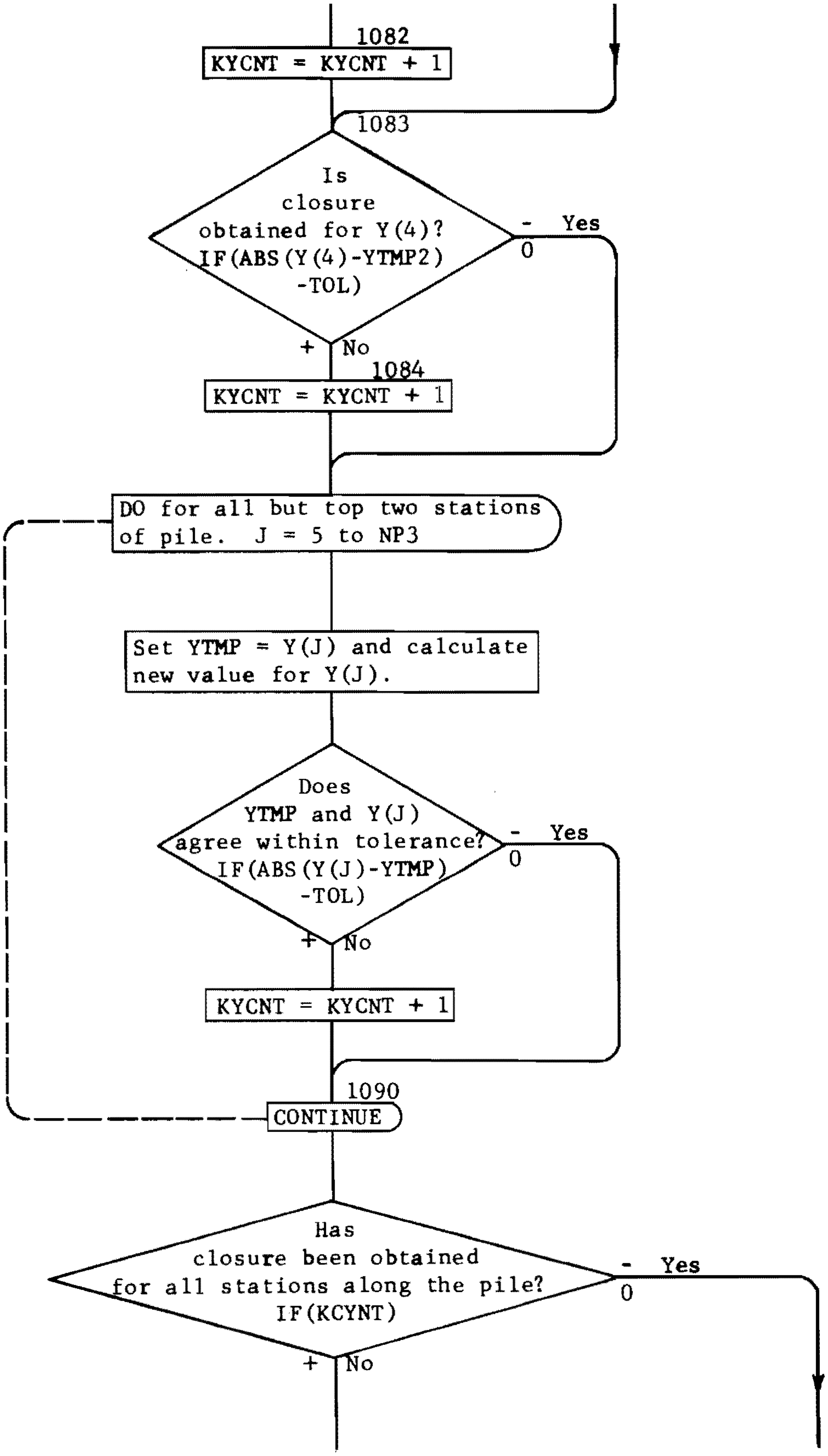
Calculate coefficients for the solution of finite difference equations.

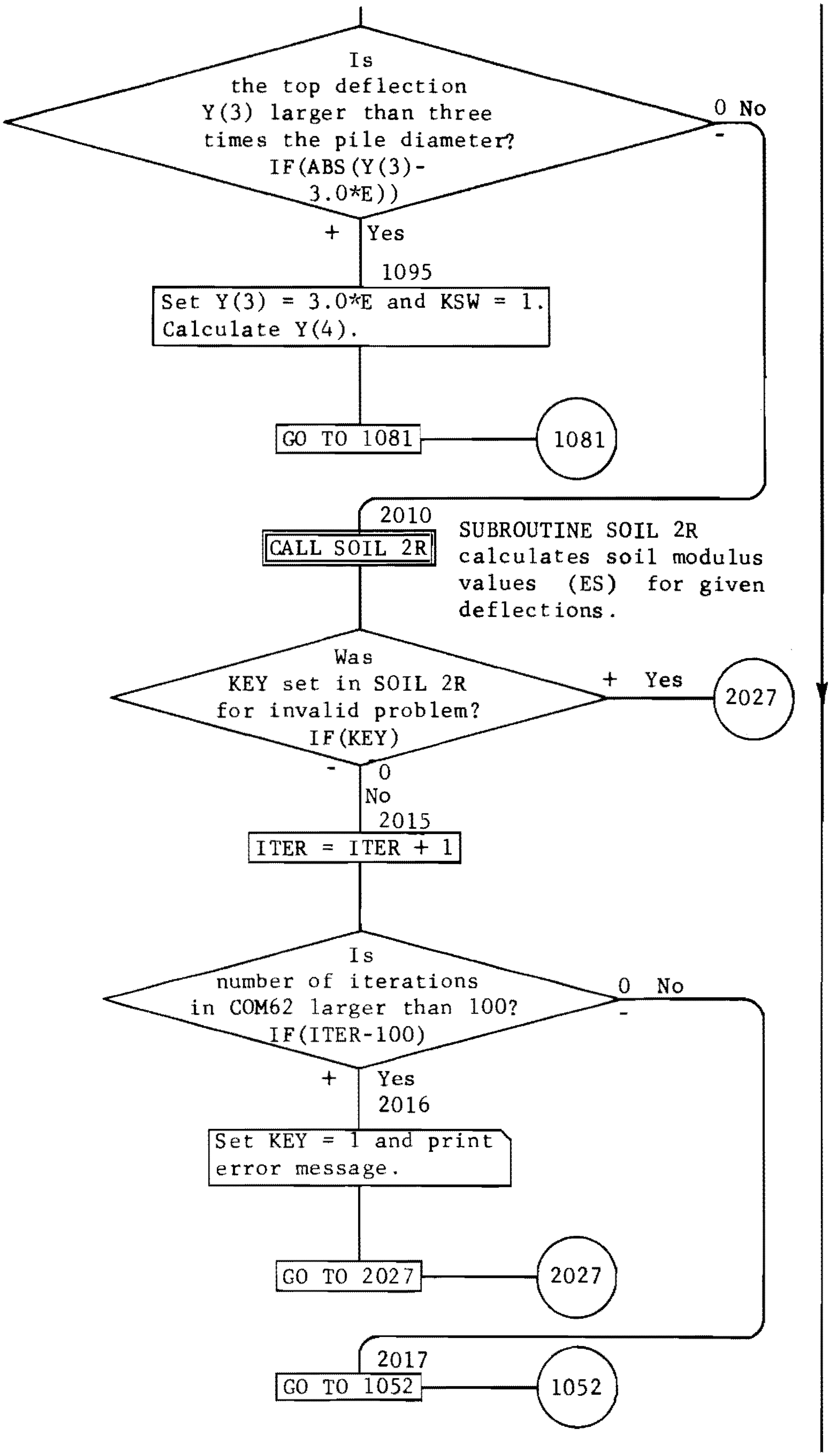


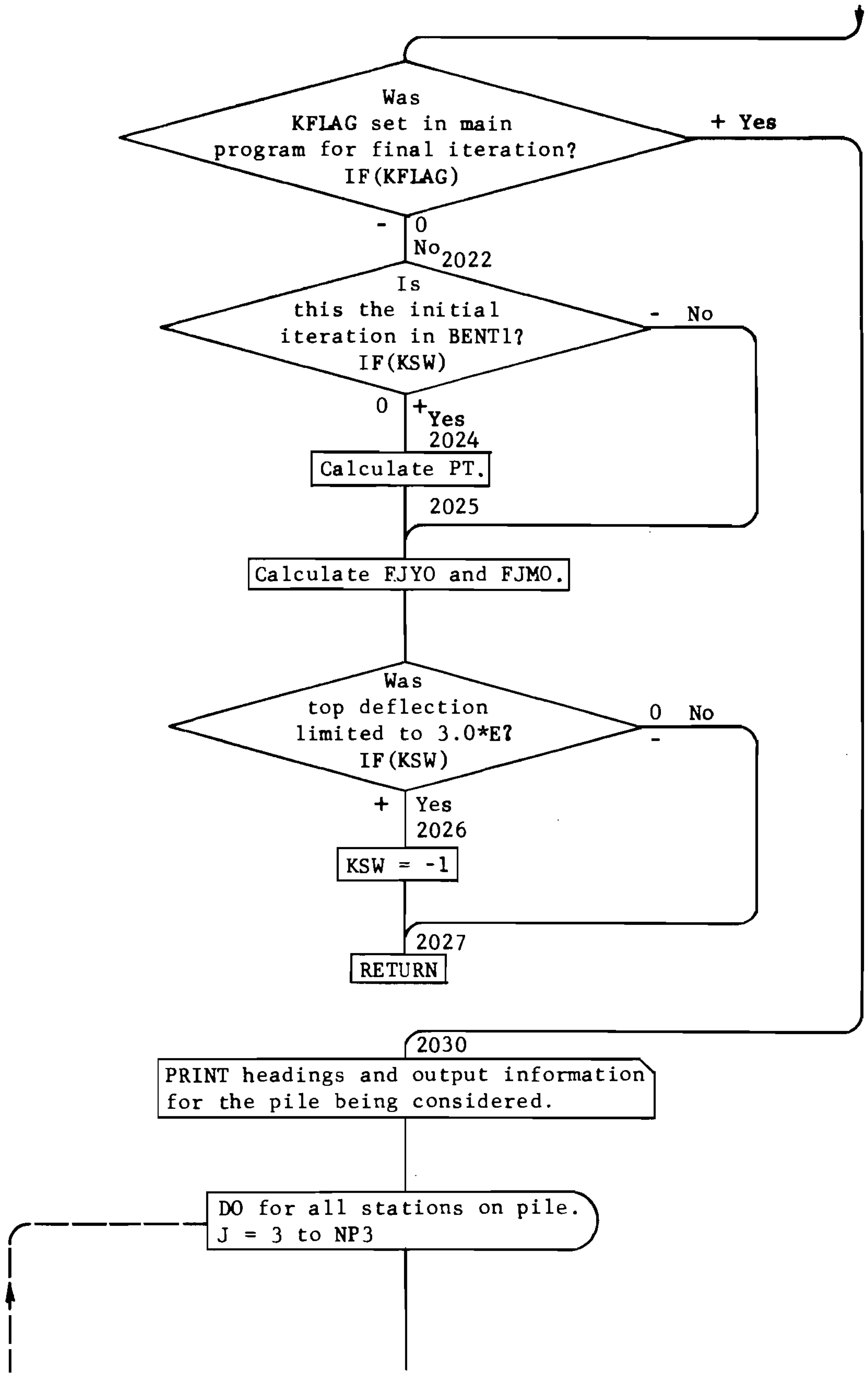
Calculate Y(3) and Y(4) which are the deflections of top two stations on pile. Equations used will depend on iteration number and top connection.

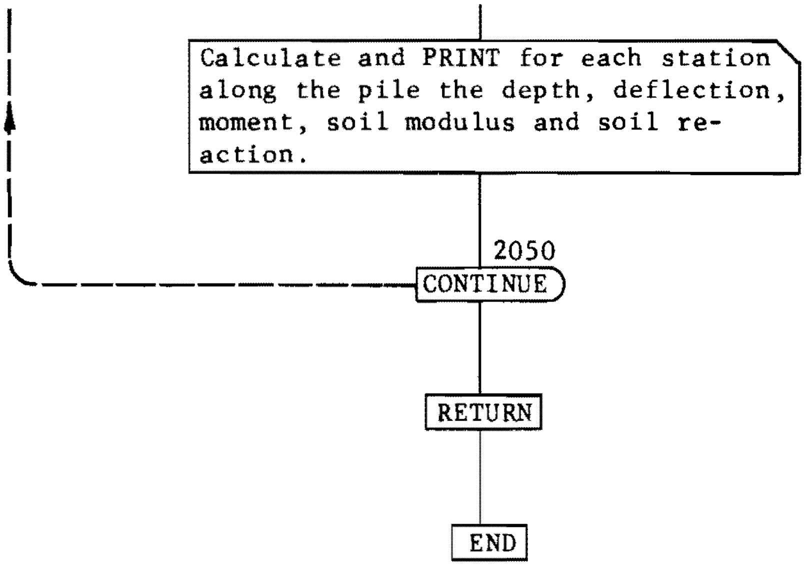


Check closure for lateral pile deflections.


1082
KYCNT = KYCNT + 1
1083
Is closure obtained for Y(4)? IF(ABS(Y(4)-YTMP2)-TOL)
-
Yes
0
+
No
1084
KYCNT = KYCNT + 1
DO for all but top two stations of pile. J = 5 to NP3
Set YTMP = Y(J) and calculate new value for Y(J).
Does YTMP and Y(J) agree within tolerance? IF(ABS(Y(J)-YTMP)-TOL)
-
Yes
0
+
No
KYCNT = KYCNT + 1
1090
CONTINUE
Has closure been obtained for all stations along the pile? IF(KCYNT)
-
Yes
0
+
No

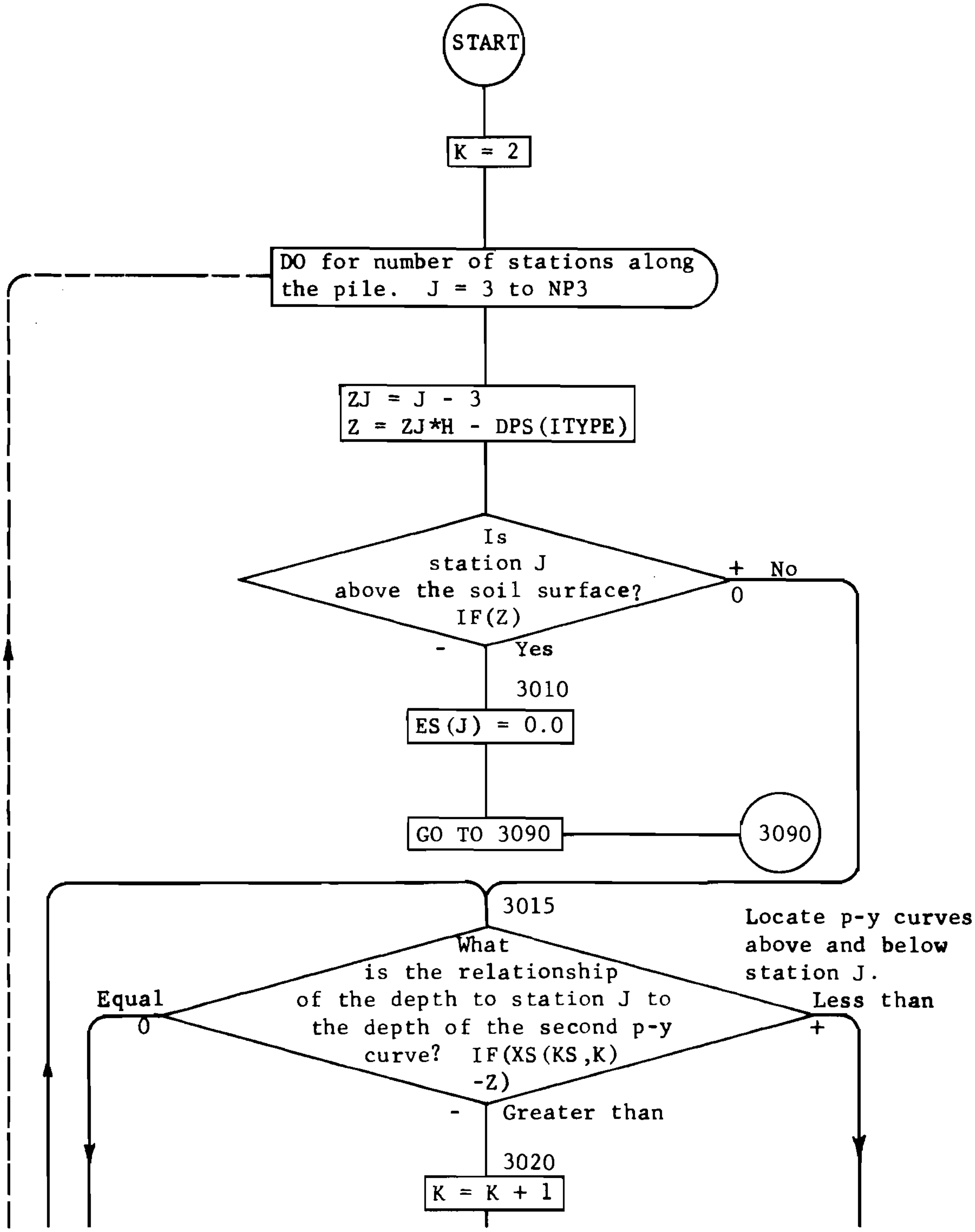

Is
the top deflection
Y(3) larger than three
times the pile diameter?
IF(ABS(Y(3)-
3.0*E))
0 No
-
+
Yes
1095
Set Y(3) = 3.0*E and KSW = 1.
Calculate Y(4).
GO TO 1081
1081
2010
CALL SOIL 2R
SUBROUTINE SOIL 2R
calculates soil modulus
values (ES) for given
deflections.
Was
KEY set in SOIL 2R
for invalid problem?
IF(KEY)
+
Yes
2027
-
0
No
2015
ITER = ITER + 1
Is
number of iterations
in COM62 larger than 100?
IF(ITER-100)
0
No
-
+
Yes
2016
Set KEY = 1 and print
error message.
GO TO 2027
2027
2017
GO TO 1052
1052

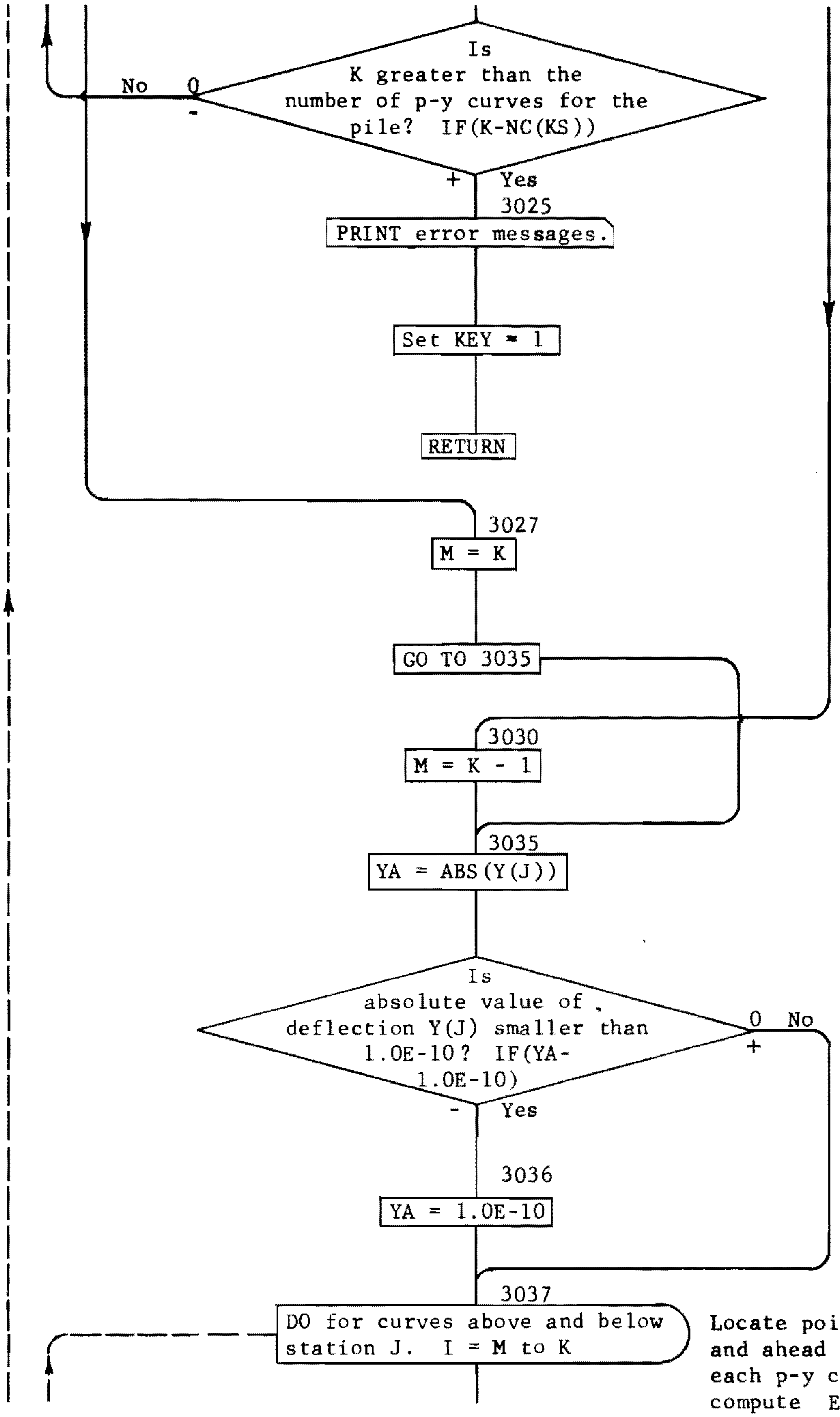

Was KFLAG set in main program for final iteration? IF(KFLAG)
+ Yes
- 0 No
2022
Is this the initial iteration in BENT1? IF(KSW)
- No
0 + Yes
2024
Calculate PT.
2025
Calculate FJYO and FJMO.
Was top deflection limited to 3.0*E? IF(KSW)
0 No -
+ Yes
2026
KSW = -1
2027
RETURN
2030
PRINT headings and output information for the pile being considered.
DO for all stations on pile. J = 3 to NP3


Calculate and PRINT for each station along the pile the depth, deflection, moment, soil modulus and soil reaction.
2050
CONTINUE
RETURN
END

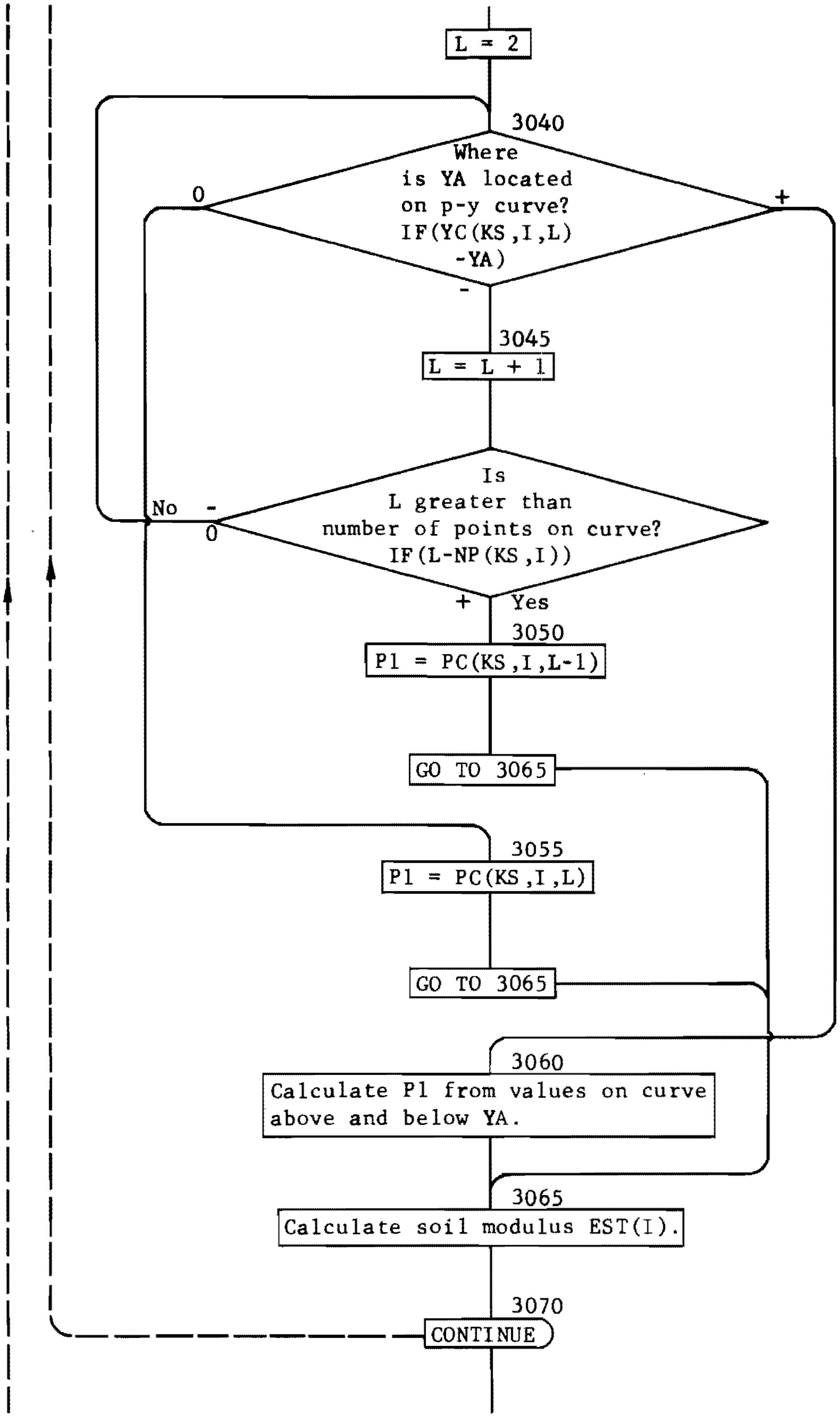
SUBROUTINE SOIL 2R

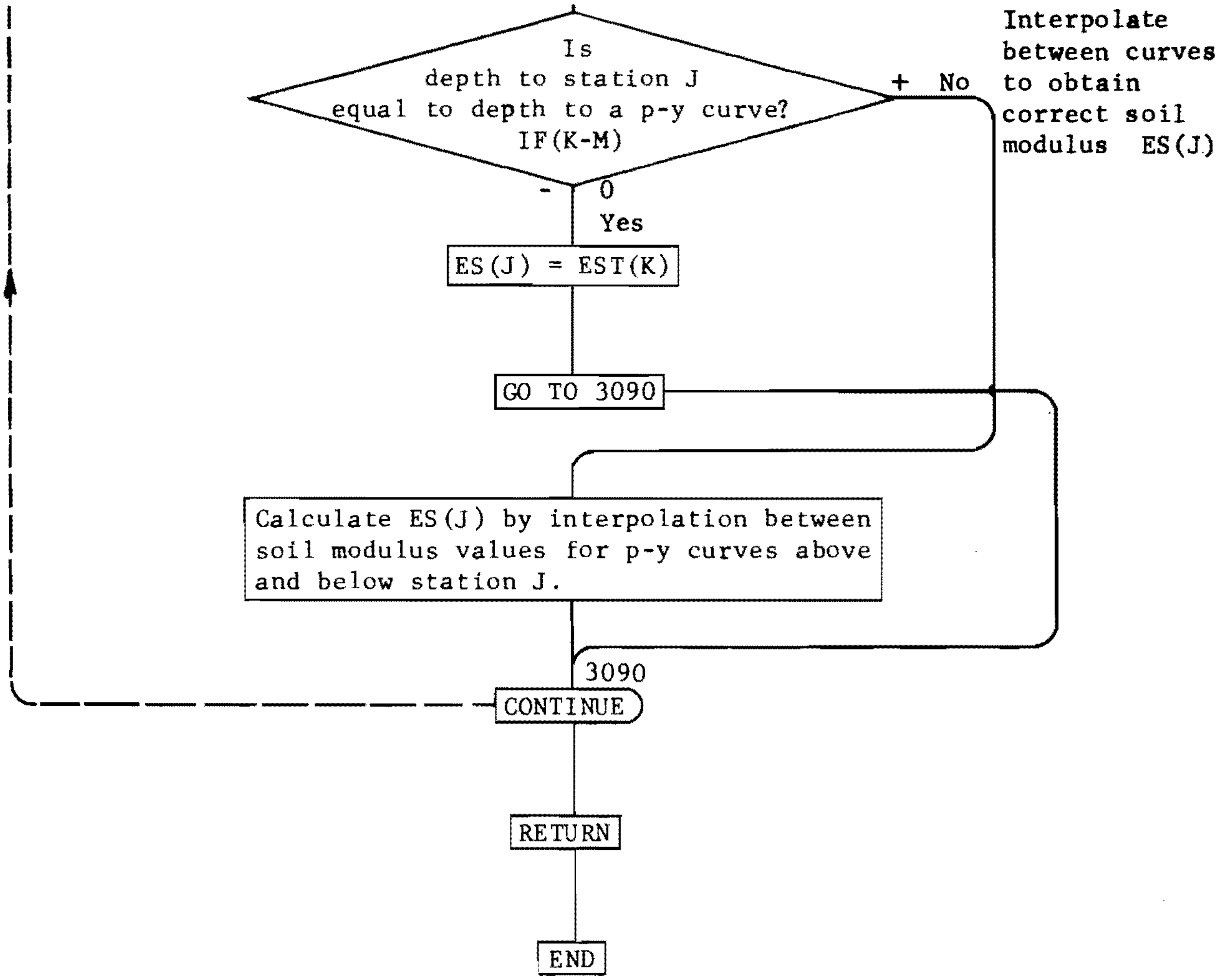
This subroutine calculates soil modulus values (ES) from given lateral deflections (Y).





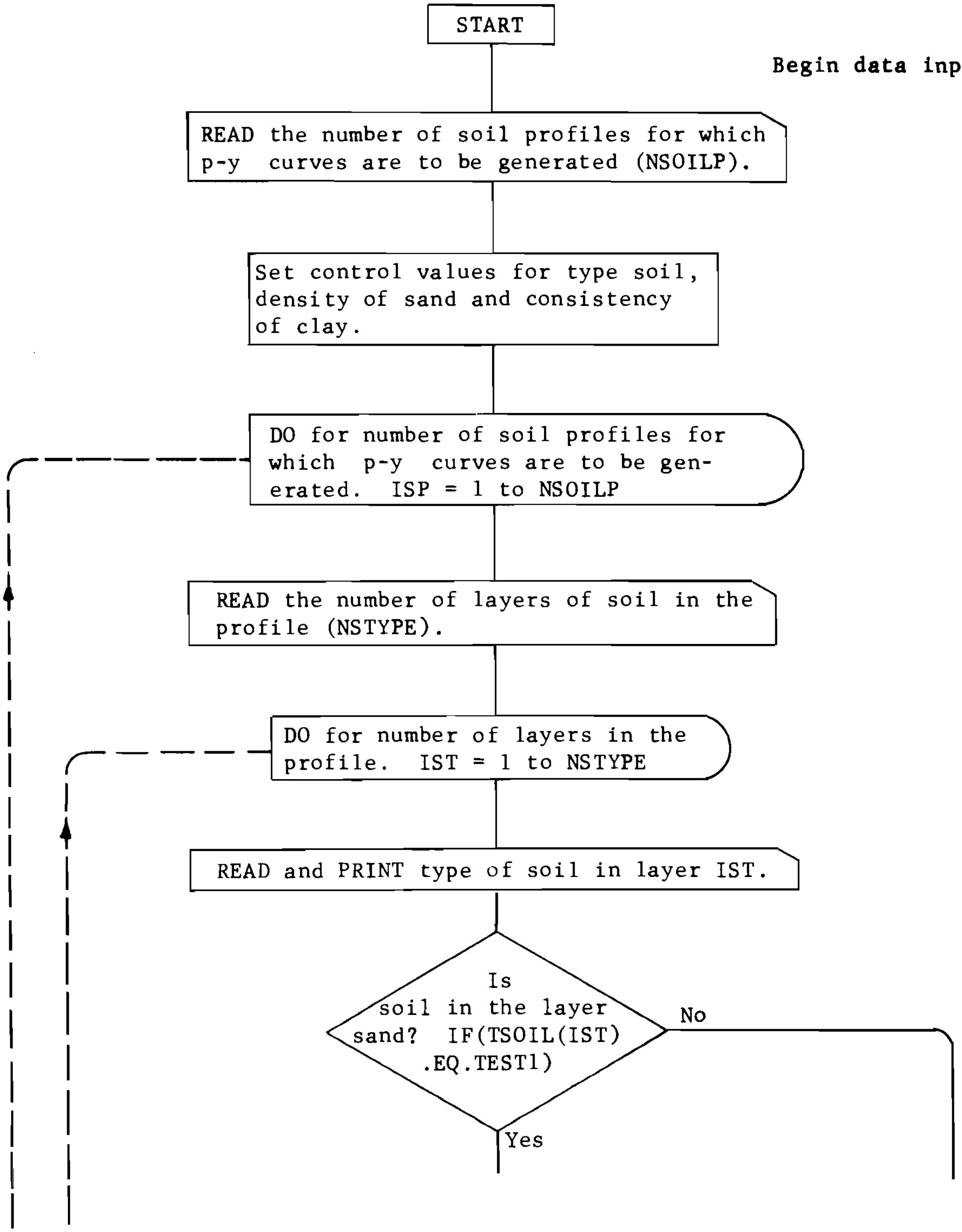
Locate points behind and ahead of YA on each p-y curve and compute ES on each curve.


L = 2
3040
Where is YA located on p-y curve? IF(YC(KS,I,L) -YA)
0
+
-
3045
L = L + 1
Is L greater than number of points on curve? IF(L-NP(KS,I))
No
-
0
+
Yes
3050
P1 = PC(KS,I,L-1)
GO TO 3065
3055
P1 = PC(KS,I,L)
GO TO 3065
3060
Calculate P1 from values on curve above and below YA.
3065
Calculate soil modulus EST(I).
3070
CONTINUE

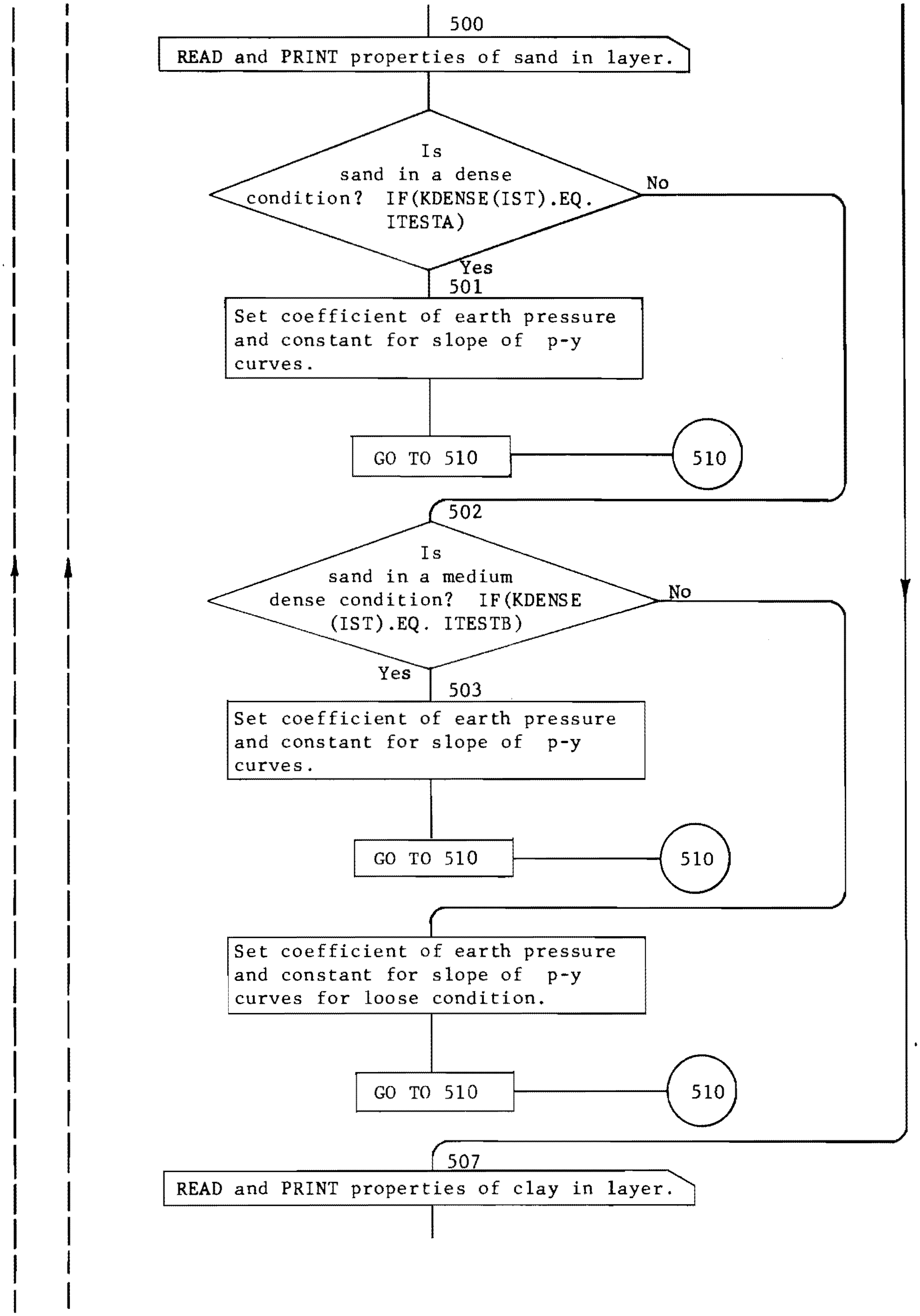

Is depth to station J equal to depth to a p-y curve? IF(K-M)
Interpolate between curves to obtain correct soil modulus ES(J)
+ No
-
0
Yes
ES(J) = EST(K)
GO TO 3090
Calculate ES(J) by interpolation between soil modulus values for p-y curves above and below station J.
3090
CONTINUE
RETURN
END

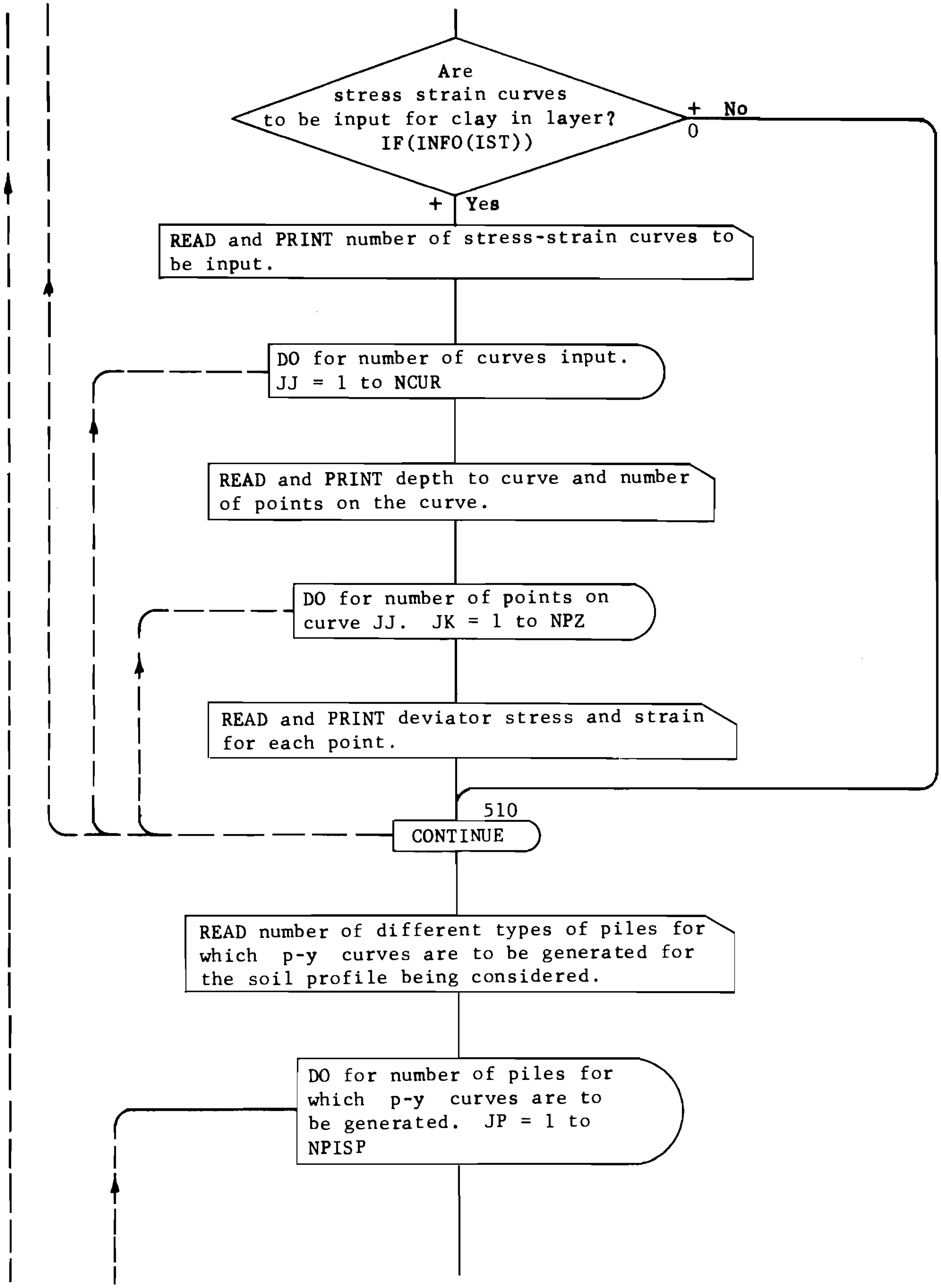
SUBROUTINE MAKE

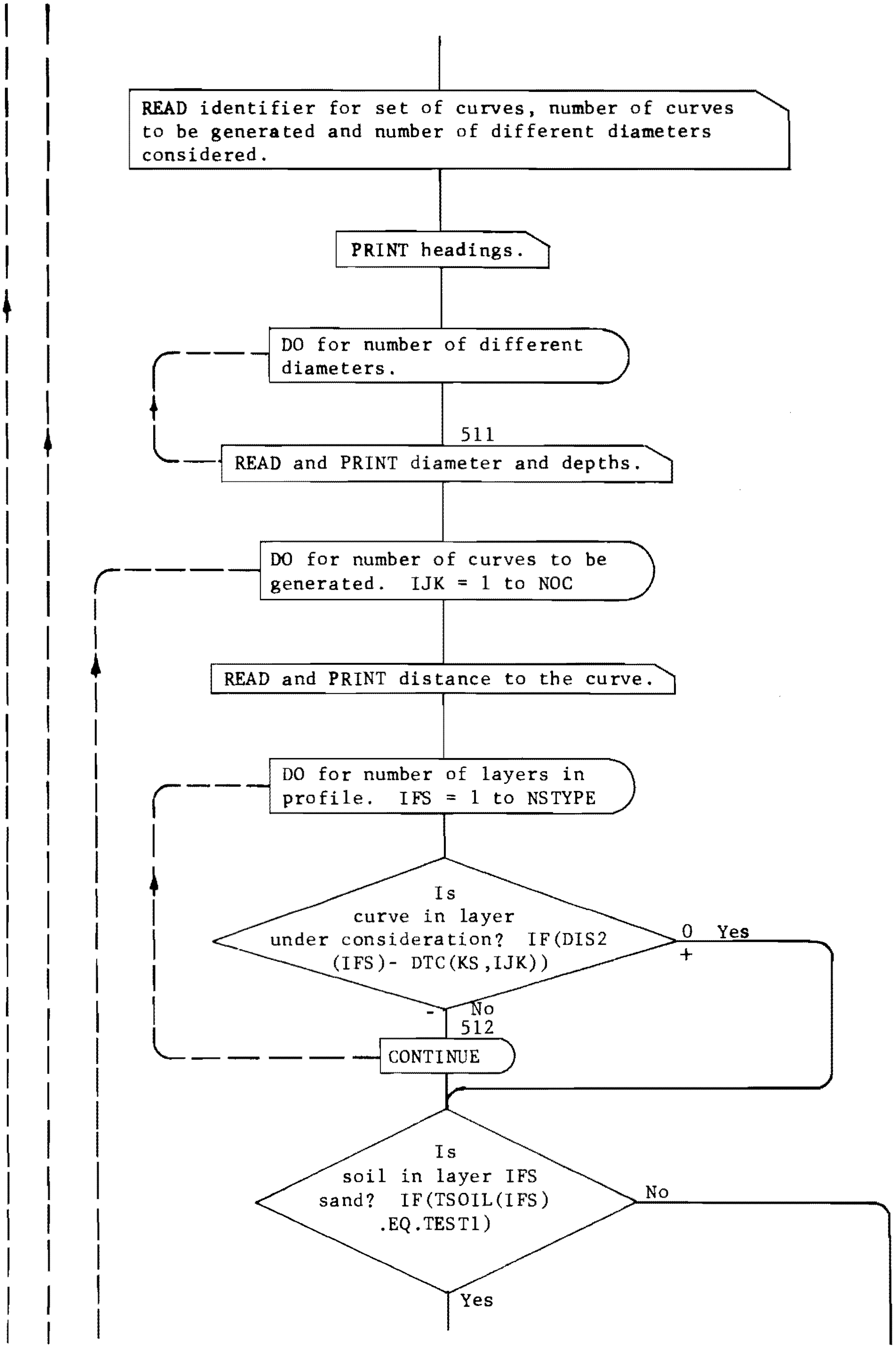
This subroutine generates p-y curves from soil properties.

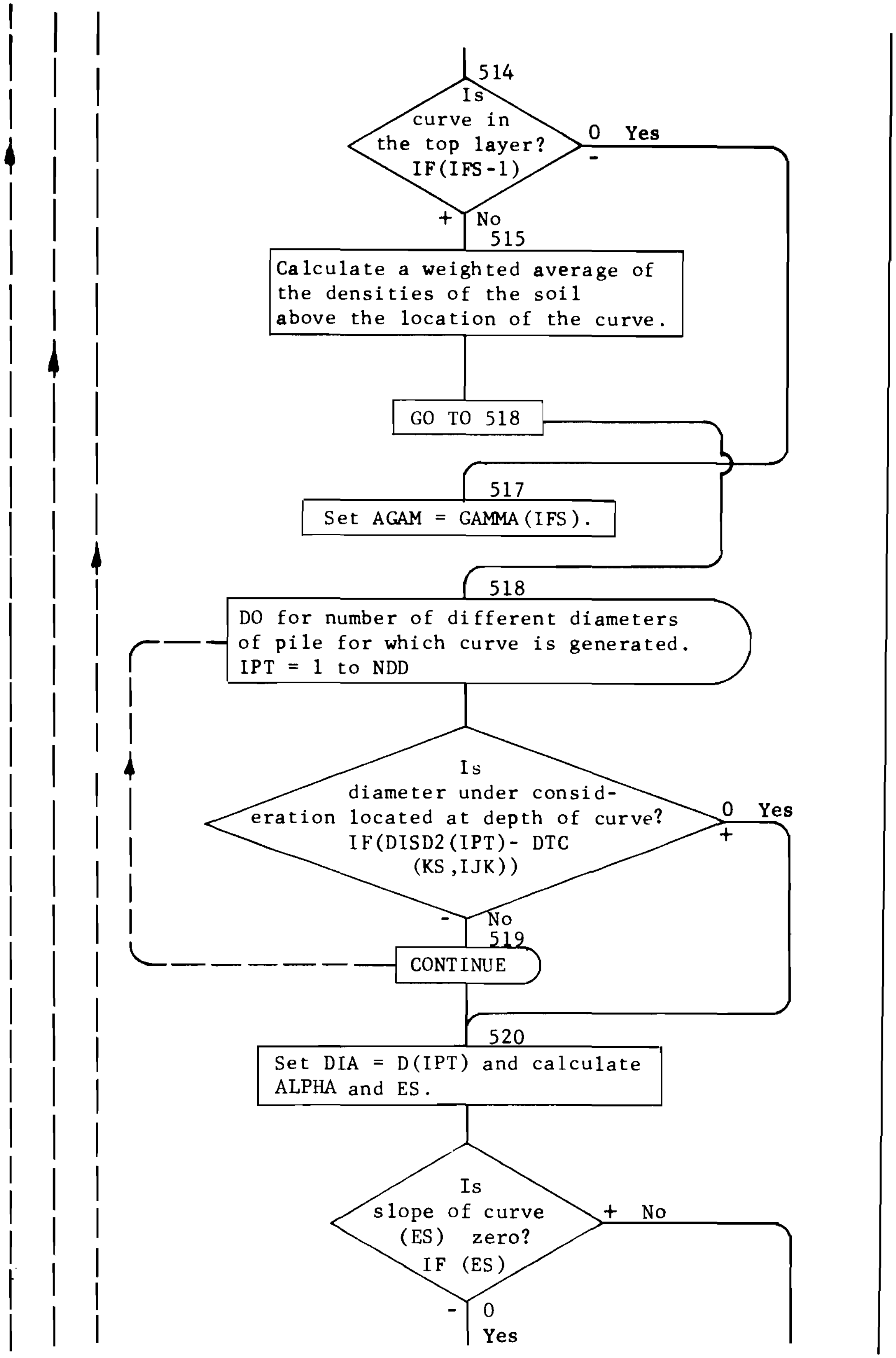


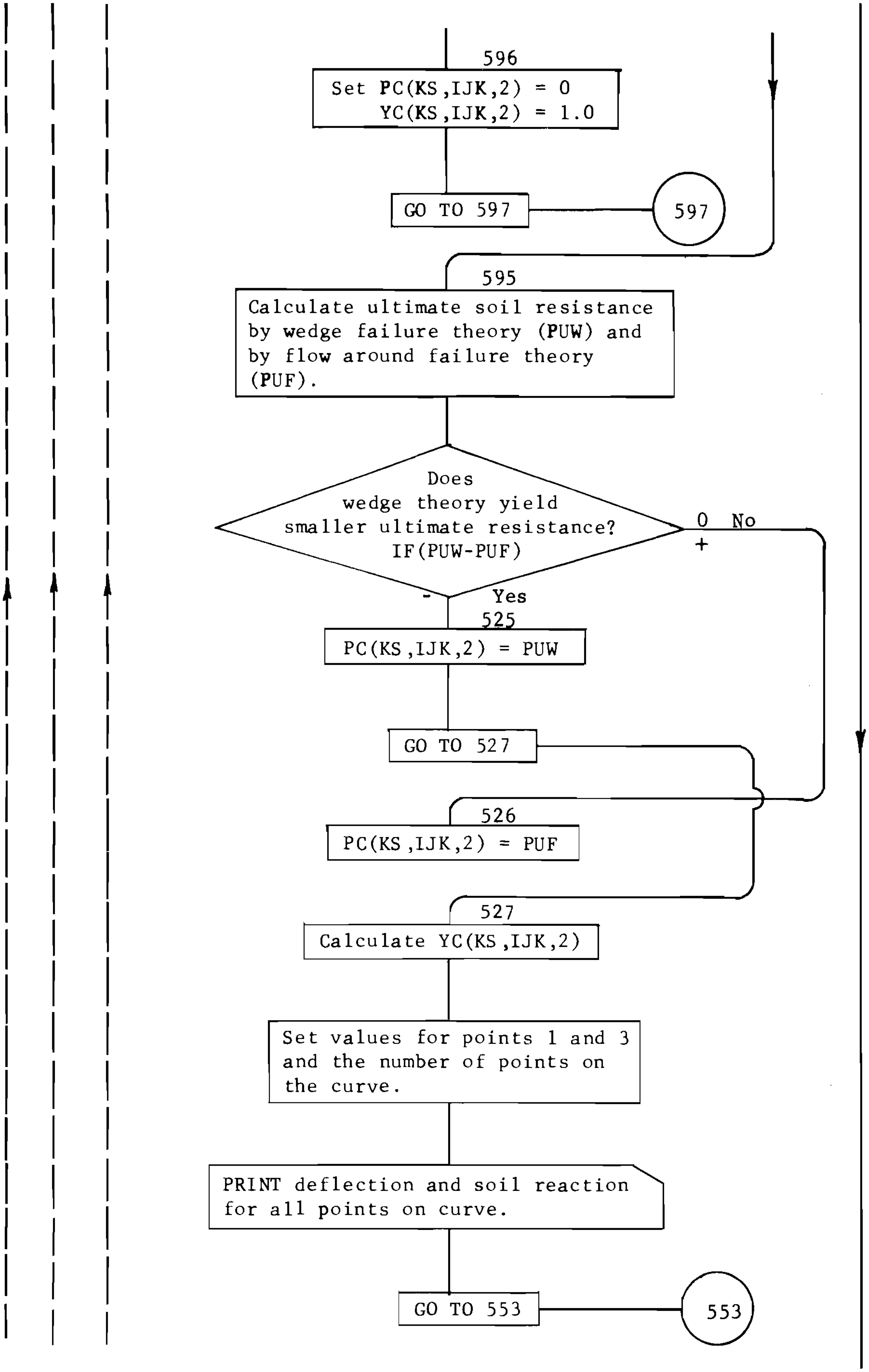
Begin data input.

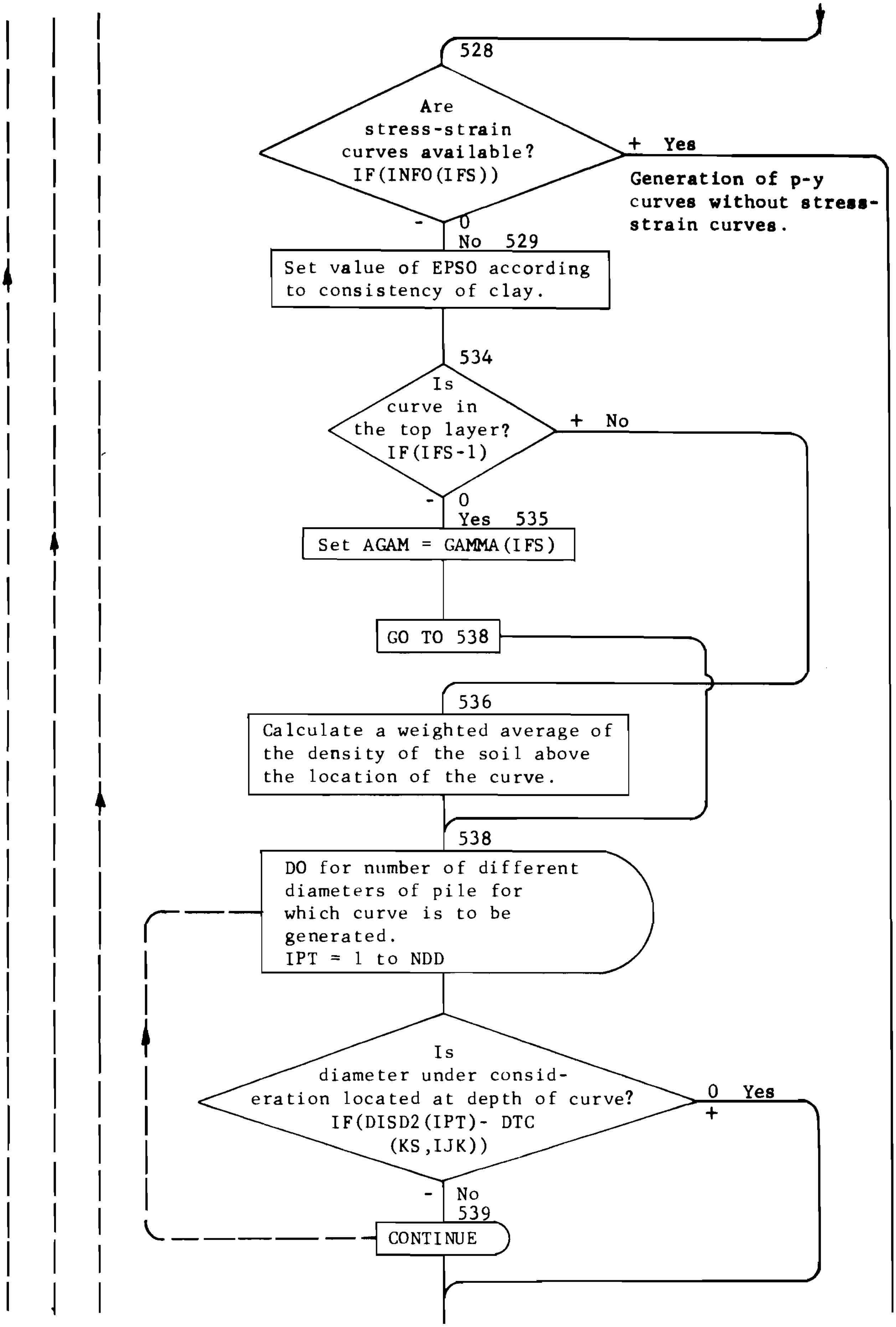

500
READ and PRINT properties of sand in layer.
Is sand in a dense condition? IF(KDENSE(IST).EQ. ITESTA)
No
Yes
501
Set coefficient of earth pressure and constant for slope of p-y curves.
GO TO 510
510
502
Is sand in a medium dense condition? IF(KDENSE (IST).EQ. ITESTB)
No
Yes
503
Set coefficient of earth pressure and constant for slope of p-y curves.
GO TO 510
510
Set coefficient of earth pressure and constant for slope of p-y curves for loose condition.
GO TO 510
510
507
READ and PRINT properties of clay in layer.

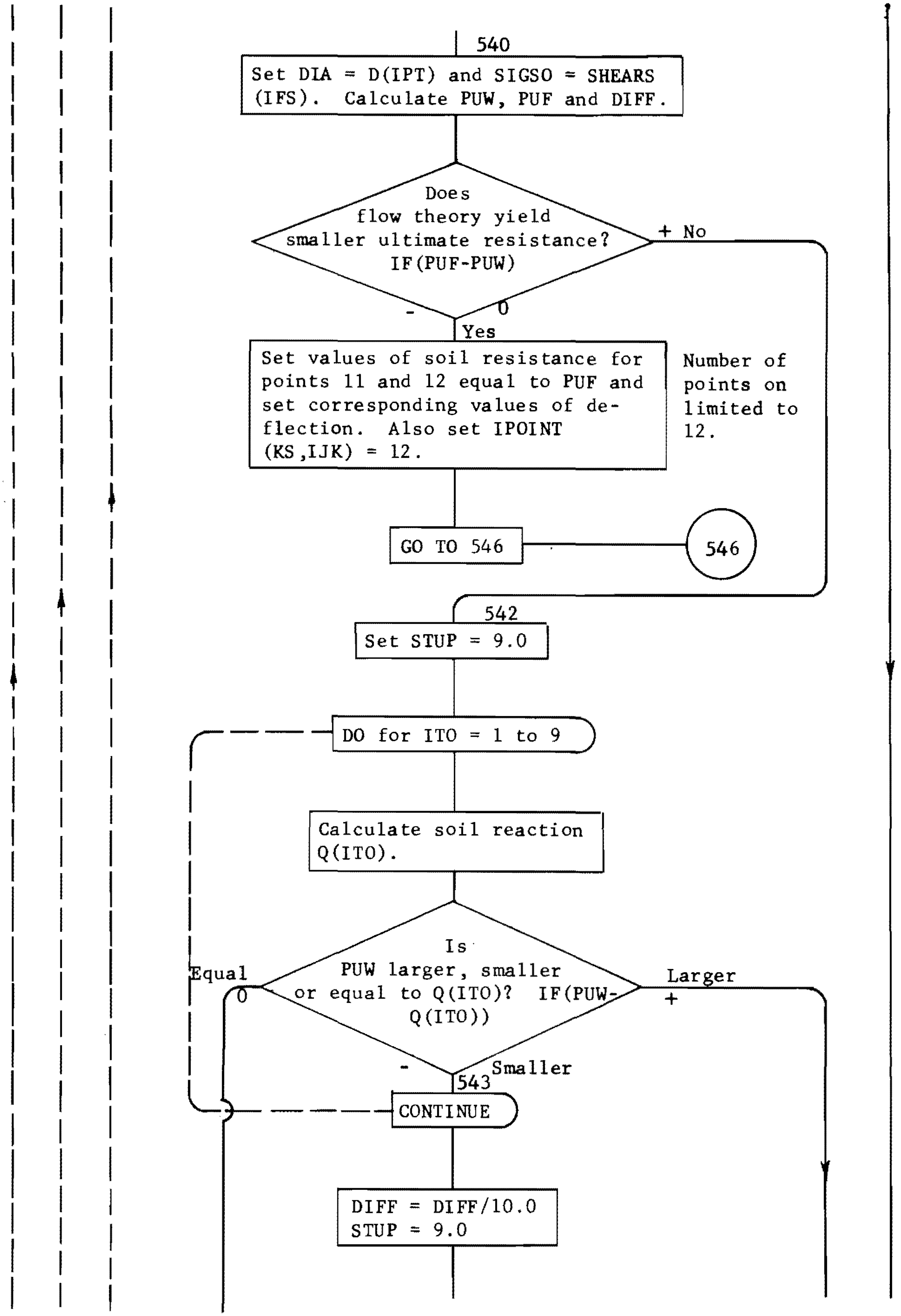

Are stress strain curves to be input for clay in layer? IF(INFO(IST))
+ No
0
+ Yes
READ and PRINT number of stress-strain curves to be input.
DO for number of curves input. JJ = 1 to NCUR
READ and PRINT depth to curve and number of points on the curve.
DO for number of points on curve JJ. JK = 1 to NPZ
READ and PRINT deviator stress and strain for each point.
510
CONTINUE
READ number of different types of piles for which p-y curves are to be generated for the soil profile being considered.
DO for number of piles for which p-y curves are to be generated. JP = 1 to NPISP

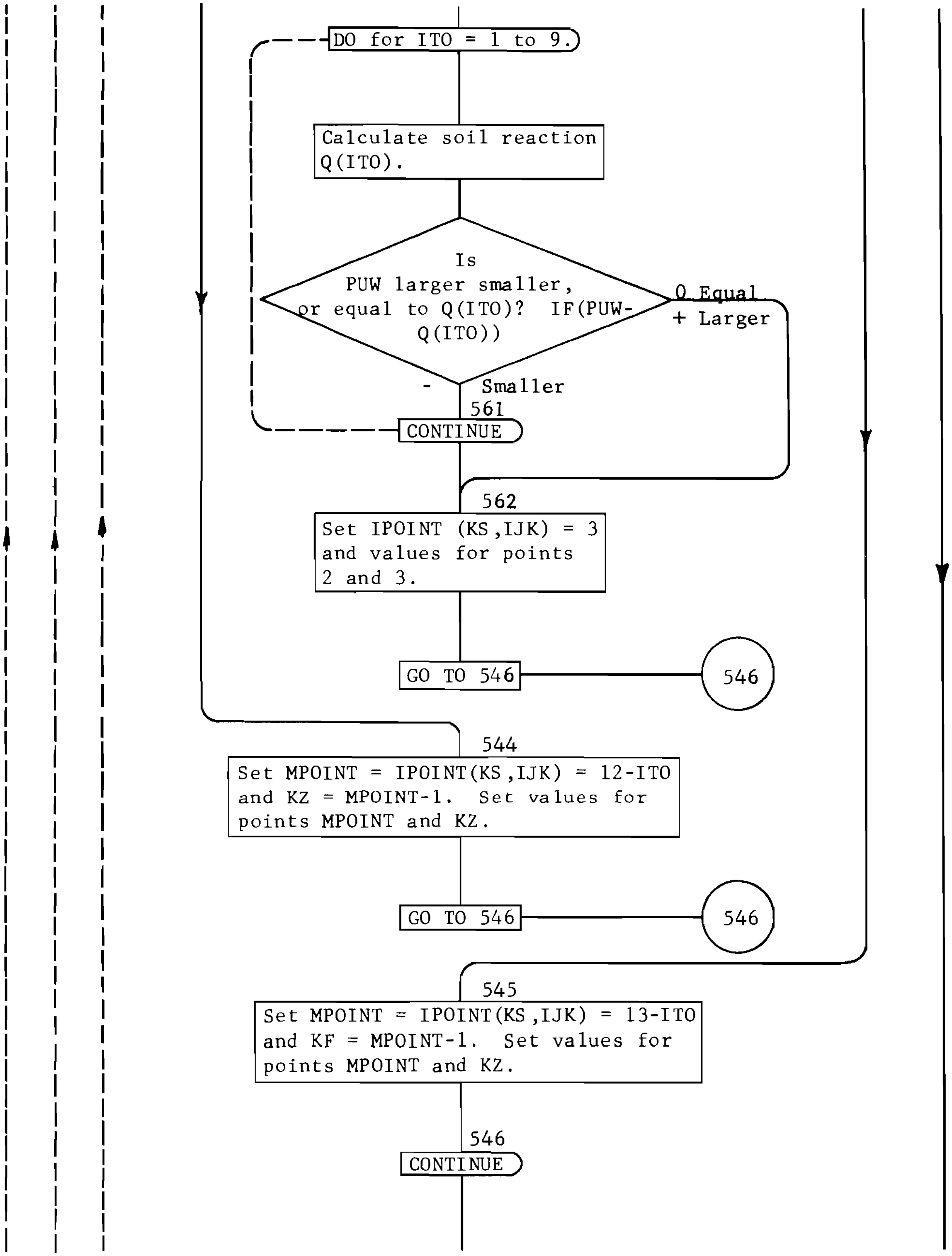

READ identifier for set of curves, number of curves to be generated and number of different diameters considered.
PRINT headings.
DO for number of different diameters.
511
READ and PRINT diameter and depths.
DO for number of curves to be generated. IJK = 1 to NOC
READ and PRINT distance to the curve.
DO for number of layers in profile. IFS = 1 to NSTYPE
Is curve in layer under consideration? IF(DIS2 (IFS)- DTC(KS,IJK))
0 Yes
+
-
No
512
CONTINUE
Is soil in layer IFS sand? IF(TSOIL(IFS) .EQ.TEST1)
No
Yes

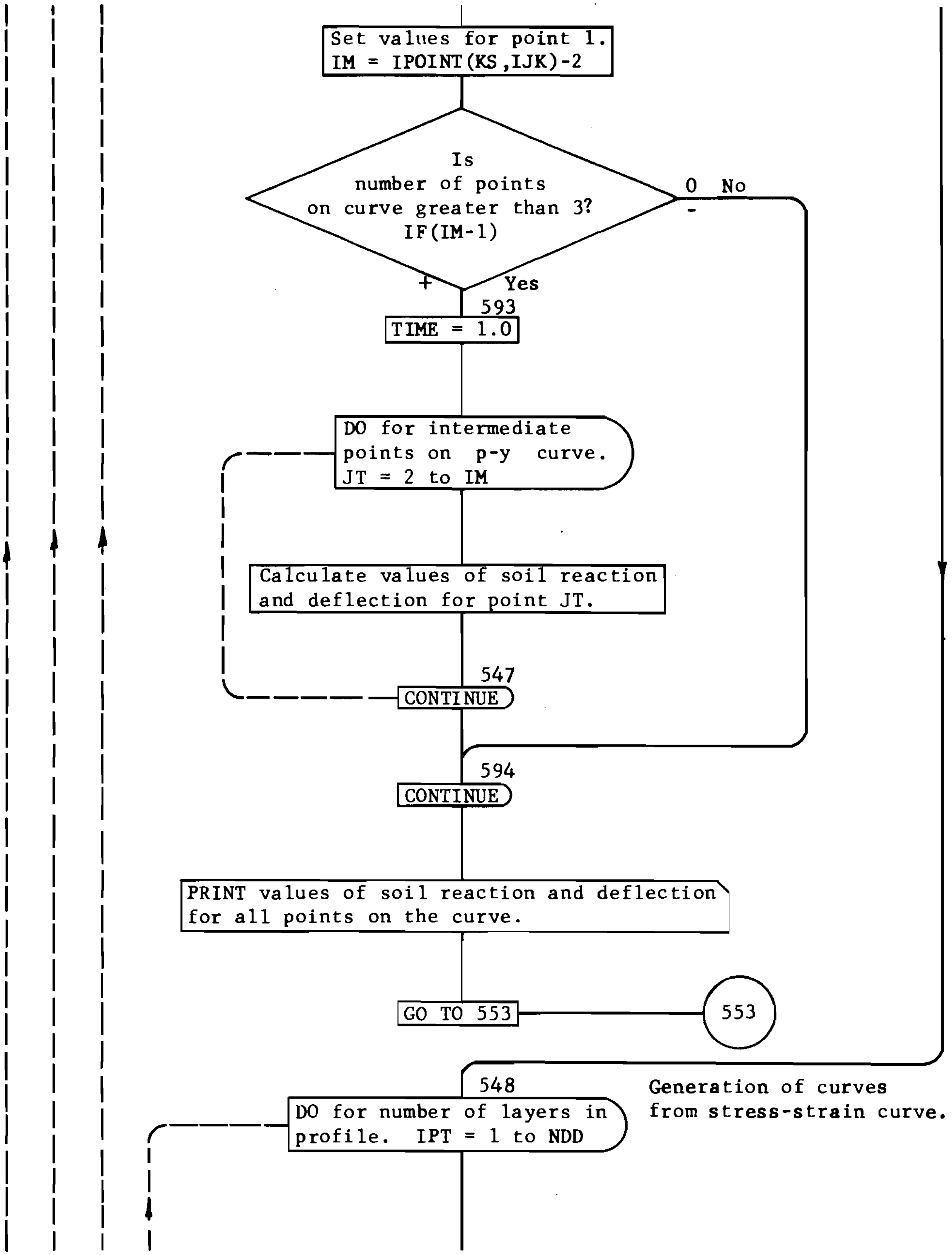

514
Is curve in the top layer? IF(IFS-1)
0 Yes
-
+
No
515
Calculate a weighted average of the densities of the soil above the location of the curve.
GO TO 518
517
Set AGAM = GAMMA(IFS).
518
DO for number of different diameters of pile for which curve is generated. IPT = 1 to NDD
Is diameter under consideration located at depth of curve? IF(DISD2(IPT)- DTC (KS,IJK))
0 Yes
+
-
No
519
CONTINUE
520
Set DIA = D(IPT) and calculate ALPHA and ES.
Is slope of curve (ES) zero? IF (ES)
+ No
-
0
Yes


596
Set PC(KS,IJK,2) = 0
YC(KS,IJK,2) = 1.0
GO TO 597
597
595
Calculate ultimate soil resistance by wedge failure theory (PUW) and by flow around failure theory (PUF).
Does wedge theory yield smaller ultimate resistance? IF(PUW-PUF)
0 No
+
-
Yes
525
PC(KS,IJK,2) = PUW
GO TO 527
526
PC(KS,IJK,2) = PUF
527
Calculate YC(KS,IJK,2)
Set values for points 1 and 3 and the number of points on the curve.
PRINT deflection and soil reaction for all points on curve.
GO TO 553
553

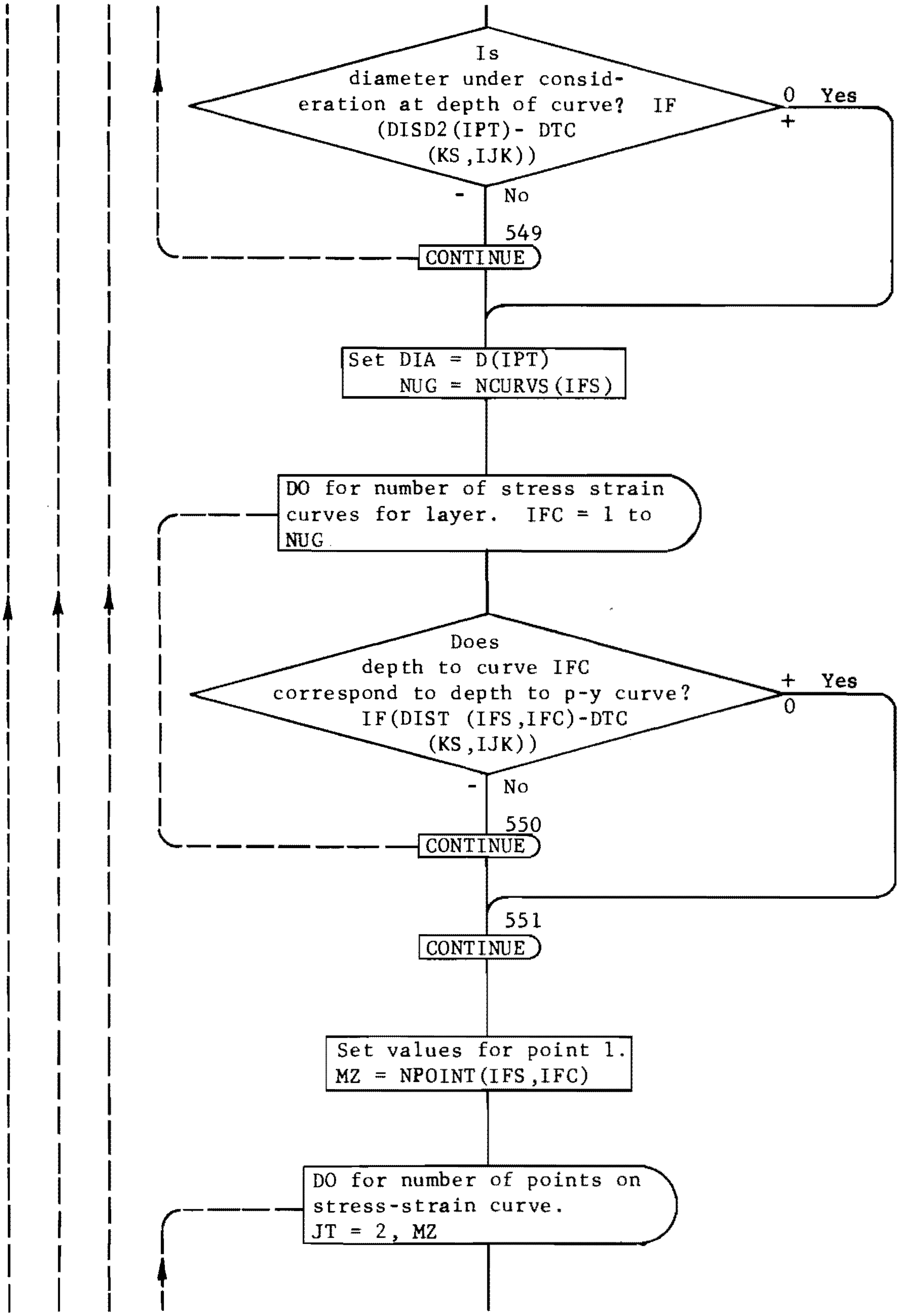

528
Are stress-strain curves available? IF(INFO(IFS))
+ Yes
Generation of p-y curves without stress-strain curves.
- 0 No 529
Set value of EPSO according to consistency of clay.
534
Is curve in the top layer? IF(IFS-1)
+ No
- 0 Yes 535
Set AGAM = GAMMA(IFS)
GO TO 538
536
Calculate a weighted average of the density of the soil above the location of the curve.
538
DO for number of different diameters of pile for which curve is to be generated. IPT = 1 to NDD
Is diameter under consideration located at depth of curve? IF(DISD2(IPT)- DTC (KS,IJK))
0 Yes +
- No 539
CONTINUE

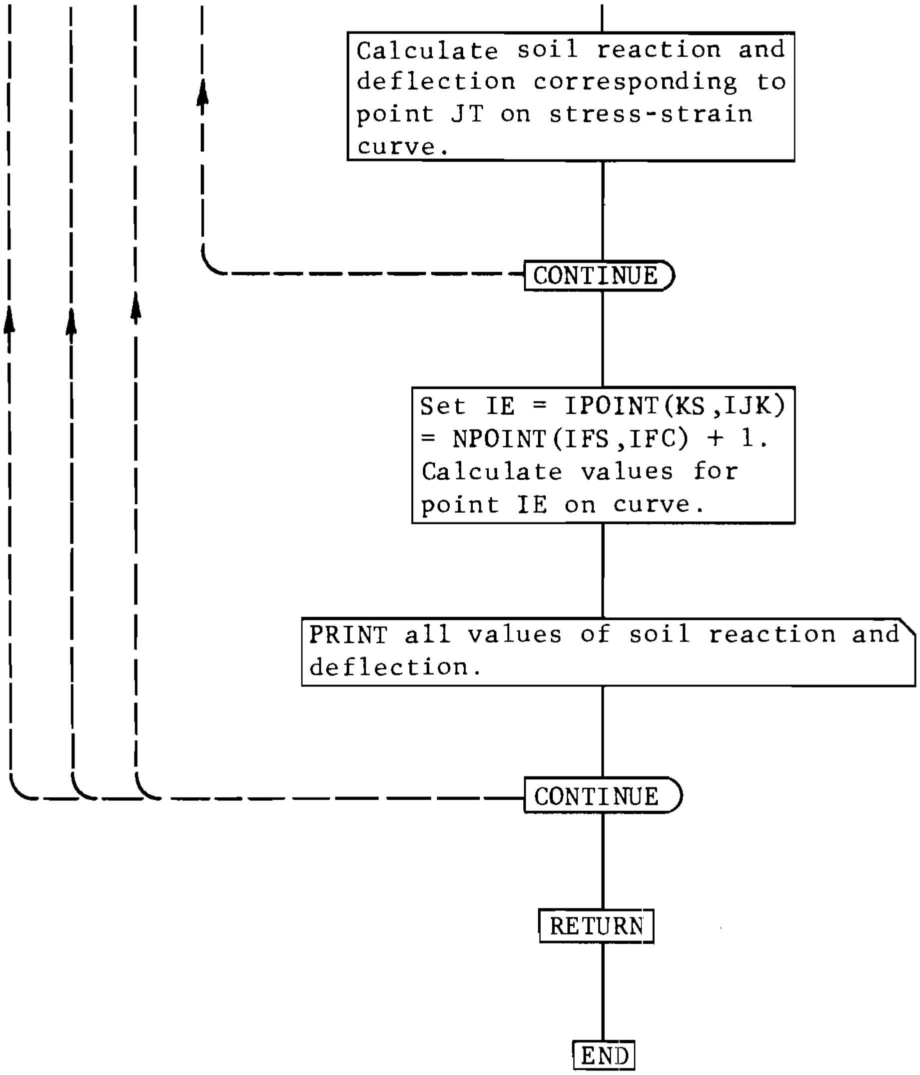

540
Set DIA = D(IPT) and SIGSO = SHEARS (IFS). Calculate PUW, PUF and DIFF.
Does flow theory yield smaller ultimate resistance? IF(PUF-PUW)
+ No
-
0
Yes
Set values of soil resistance for points 11 and 12 equal to PUF and set corresponding values of deflection. Also set IPOINT (KS,IJK) = 12.
Number of points on limited to 12.
GO TO 546
546
542
Set STUP = 9.0
DO for ITO = 1 to 9
Calculate soil reaction Q(ITO).
Is PUW larger, smaller or equal to Q(ITO)? IF(PUW-Q(ITO))
Equal
0
Larger
+
-
Smaller
543
CONTINUE
DIFF = DIFF/10.0
STUP = 9.0


DO for ITO = 1 to 9.
Calculate soil reaction Q(ITO).
Is PUW larger smaller, or equal to Q(ITO)? IF(PUW-Q(ITO))
0 Equal
+ Larger
-
Smaller
561
CONTINUE
562
Set IPOINT (KS,IJK) = 3 and values for points 2 and 3.
GO TO 546
546
544
Set MPOINT = IPOINT(KS,IJK) = 12-ITO and KZ = MPOINT-1. Set values for points MPOINT and KZ.
GO TO 546
546
545
Set MPOINT = IPOINT(KS,IJK) = 13-ITO and KF = MPOINT-1. Set values for points MPOINT and KZ.
546
CONTINUE



Generation of curves from stress-strain curve.


Is diameter under consideration at depth of curve? IF (DISD2(IPT)- DTC (KS,IJK))
0 Yes
+
- No
549
CONTINUE
Set DIA = D(IPT)
NUG = NCURVS(IFS)
DO for number of stress strain curves for layer. IFC = 1 to NUG
Does depth to curve IFC correspond to depth to p-y curve? IF(DIST (IFS,IFC)-DTC (KS,IJK))
+ Yes
0
- No
550
CONTINUE
551
CONTINUE
Set values for point 1.
MZ = NPOINT(IFS,IFC)
DO for number of points on stress-strain curve.
JT = 2, MZ


Calculate soil reaction and deflection corresponding to point JT on stress-strain curve.
CONTINUE
Set IE = IPOINT(KS,IJK) = NPOINT(IFS,IFC) + 1. Calculate values for point IE on curve.
PRINT all values of soil reaction and deflection.
CONTINUE
RETURN
END

APPENDIX C

GLOSSARY OF NOTATION FOR BENT1

NOTATION FOR BENT1

THE FOLLOWING VARIABLES ARE INPUT AS DATA FOR THE MAIN PROGRAM

ANUM	ALPHANUMERIC IDENTIFICATION--ONE 80 COLUMN CARD DESCRIBING THE PROBLEM
PV	VERTICAL LOAD ON BENT THROUGH ORIGIN OF COORDINATES
PH	HORIZ LOAD ON BENT THROUGH ORIGIN OF COORDINATES
TM	MOMENT APPLIED TO BENT ABOUT ORIGIN OF COORDINATES
TOL	ITERATION TOLERANCE--CONTROLS FOR LATERALLY LOADED PILE ROUTINE AND TRANSLATION OF BENT--MULTIPLIED BY 0.001 FOR ROTATION OF BENT
KNPL	NUMBER OF PILE LOCATIONS IN BENT
KOSC	SWITCH TO CONTROL OSCILLATING SOLUTIONS--SET TO ZERO FOR NORMAL USE--IF BENT MOVEMENTS OSCILLATE SET EQUAL TO ONE
DISTA	HORIZONTAL COORDINATE OF PILE HEAD
DISTB	VERTICAL COORDINATE OF PILE HEAD
THETA	BATTER OF PILE MEASURED FROM VERTICAL--NEGATIVE CLOCKWISE
POTT	NUMBER OF PILES OF A PARTICULAR TYPE AT A PILE LOCATION
KS	IDENTIFIER TO RELATE A PILE TO A SET OF PY CURVES
KA	IDENTIFIER TO RELATE A PILE TO AN AXIAL LOAD SETTLEMENT CURVE
HH	INCREMENT LENGTH FOR PILE
NN	NUMBER OF INCREMENTS INTO WHICH PILE IS DIVIDED
DPS	DISTANCE FROM PILE TOP TO SOIL SURFACE
NDEI	NUMBER OF DIFFERENT STIFFNESS VALUES FOR PILE
TC	ALPHANUMERIC DESIGNATION OF MANNER IN WHICH PILE IS CONNECTED TO STRUCTURE--FIX,PIN,OR RES
FDBET	ROTATIONAL RESTRAINT--MOMENT DIVIDED BY ANGLE CHANGE--MAY BE LEFT BLANK IF TC=FIX OR TC=PIN
RRI	FLEXURAL STIFFNESS (EI)
XX1	DISTANCE FROM TOP OF PILE TO TOP OF SECTION OF PILE WITH A CERTAIN FLEXURAL STIFFNESS
XX2	DISTANCE FROM TOP OF PILE TO BOTTEM OF SECTION OF PILE WITH A CERTAIN FLEXURAL STIFFNESS
NKA	NUMBER OF AXIAL LOAD SETTLEMENT CURVES INPUT
NKS	NUMBER OF SETS OF P-Y CURVES INPUT--LEFT BLANK IF KOK=1
KOK	SWITCH FOR INPUT OF P-Y CURVES--KOK=1 NUMERICAL P-Y CURVES INPUT--KOK=0 P-Y CURVES GENERATED FROM SOIL PROPERTIES
IDEN	IDENTIFIER FOR LOAD SETTLEMENT CURVE
IO	NO. OF POINTS ON LOAD SETTLEMENT CURVE
ZZZ	SETTLEMENT ON AXIAL LOAD SETTLEMENT CURVE
SSS	AXIAL LOAD ON AXIAL LOAD SETTLEMENT CURVE
IDPY	IDENTIFIER FOR SET OF P-Y CURVES
KNC	NUMBER OF CURVES IN A SET OF P-Y CURVES
NP	NUMBER OF POINTS ON A P-Y CURVE
XS	DISTANCE FROM SOIL SURFACE TO P-Y CURVE
YC	DEFLECTION ON P-Y CURVE
PC	SOIL RESISTANCE ON P-Y CURVE
E	PILE DIAMETER AT TOP OF PILE

THE FOLLOWING VARIABLES ARE INPUT DATA FOR SUBROUTINE MAKE

NSOILP	NUMBER OF SOIL PROFILES FOR WHICH P-Y CURVES ARE GENERATED
NSTYPE	NUMBER OF SOIL LAYERS IN A SOIL PROFILE
DIS1	DISTANCE FROM SURFACE TO TOP OF STRATUM
DIS2	DISTANCE FROM SURFACE TO BOTTEM OF STRATUM
TSOIL	ALPHANUMERIC IDENTIFIER FOR TYPE OF SOIL IN A STRATUM
GAMMA	UNIT WEIGHT OF SOIL IN A STRATUM
PHI	ANGLE OF INTERNAL FRICTION FOR A SAND
KDENSE	ALPHANUMERIC IDENTIFIER FOR RELATIVE DENSITY OF SAND
SHEARS	SHEAR STRENGTH FOR CLAY
INFO	VARIABLE TO CONTROL INPU OF STRESS STRAIN CURVES FOR A CLAY--INFO=0 NO CURVES INPUT , INFO=1 CURVES INPUT
ICON	ALPHANUMERIC IDENTIFIER FOR CONSISTENCY OF CLAY
NCURVS	NUMBER OF STRESS-STRAIN CURVES INPUT
DIST	DISTANCE FROM SURFACE TO A CURVE
NPOINT	NUMBER OF POINTS ON A CURVE
SIGD	DEVIATOR STRESS
FP	STRAIN
NPISP	NUMBER OF SETS OF P-Y CURVES GENERATED FROM A SOIL PROFILE
NOC	NUMBER OF CURVES GENERATED FOR A PARTICULAR SET OF CURVES
NDD	NUMBER OF SECTIONS WITH DIFFERENT DIAMETERS IN A PILE
D	DIAMETER OF A SECTION OF PILE
DISD1	DISTANCE FROM SURFACE TO TOP OF SECTION
DISD2	DISTANCE FROM SURFACE TO BOTTEM OF SECTION
DTC	DISTANCE FROM SURFACE TO P-Y CURVE

THE FOLLOWING ARE ADDITIONAL VARIABLES USED IN THE MAIN PROGRAM

KFLAG	ROUTING SWITCH CONTROLLED BY CLOSURE
KEY	ROUTING SWITCH CONTROLLED BY INVALID SOLUTION
KSW	ROUTING SWITCH CONTROLLED BY ITERATION NUMBER
ITER	COUNTER FOR NUMBER OF ITERATIONS--USED FOR ITERATION ON FOUNDATION MOVEMENT AND IN COM62 FOR DEFLECTION OF PILE
DV	VERTICAL FOUNDATION MOVEMENT
DH	HORIZONTAL FOUNDATION MOVEMENT
ALPHA	ROTATION OF FOUNDATION ABOUT ORIGIN OF COORDINATE SYSTEM
XT	AXIAL DEFLECTION OF PILE TOP
YT	LATERAL DEFLECTION OF PILE TOP
BC2	SECOND BOUNDRY CONDITION APPLIED TO TOP OF THE PILE FOR USE IN COM62--VALUE WILL DEPEND ON TYPE CONNECTION
PT	LATERAL LOAD APPLIED TO TOP OF PILE
FMT	MOMENT APPLIED TO TOP OF PILE
PX	AXIAL LOAD APPLIED TO TOP OF PILE
I	IDENTIFIER FOR PILE UNDER CONSIDERATION
FJX	AXIAL SPRING MODULUS
FJY	LATERAL SPRING MODULUS--CALCULATED AS FJYO IN COM62
FJM	ROTATIONAL SPRING MODULUS--CALCULATED AS FJMO IN COM62
DEN	NUMERATOR FOR CRAMERS RULE
AA ,BB ,CC ,DD ,EE	COEFFICIENTS USED IN SOLUTION OF EQUILIBRIUM EQUATIONS
A1,A2,A3,B1,B2,B3,C1,C2,C3	COEFFICIENTS USED IN SOLUTION OF EQUILIBRIUM EQUATIONS

THE FOLLOWING ADDITIONAL VARIABLES ARE USED IN SUBROUTINE MAKE

IST	IDENTIFIER FOR STRATUM UNDER CONSIDERATION
FKO	COEFFICIENTS OF EARTHPRESSURE AT REST FOR SAND
AV	CONSTANT USED IN CALCULATING COEFFICIENT OF SUBGRADE REACT
AGAM	AVERAGE UNIT WEIGHT OF SOIL ABOVE A POINT
DIA	PILE DIAMETER
ALPHA	ANGLE OF INTERNAL FRICTION DIVIDED BY TWO
ES	COEFFICIENT OF SUBGRADE REACTION
PUW	ULTIMATE SOIL RESISTANCE FROM WEDGE FAILURE
PUF	ULTIMATE SOIL RESISTANCE FROM FLOW AROUND FAILURE
EP50	ONE HALF OF STRAIN AT FAILURE
SIG50	ONE HALF OF ULTIMATE DEVIATOR STRESS
EP100	STRAIN AT FAILURE
DIFF	INCREMENT OF STRAIN
STUP	COUNTER USED TO CALCULATE STRAIN FROM INCREMENT OF STRAIN
SIGA	DEVIATOR STRESS
Q	SOIL RESISTANCE
IPOINT	NUMBER OF POINTS ON P-Y CURVE

THE FOLLOWING VARIABLES ARE USED IN SUBROUTINE COM62

ITYPE	IDENTIFIER FOR PILE UNDER COSIIDERATION
J	IDENTIFIER FOR STATION UNDER CONSIDERATION
Y	DEFLECTION AT STATION J
ES	SOIL MODULUS AT STATION J
R	PILE STIFFNESS AT STATION J
KYCNT	COUNTER USED TO CHECK CLOSURE
TMOM	MOMENT APPLIED TO PILE TOP
PLGTH	PILE LENGTH--INCHES
FMO	MOMENT AT A STATION ALONG THE PILE
RES	SOIL RESISTANCE AT A STATION ALONG THE PILE
A ,B ,C	COEFFICIENTS USED IN THE SOLUTION FOR THE DEFLECTED SHAPE OF THE PILE
S3,S4,S5	CONSTANTS CALCULATED USING APPLIED BOUNDRY COND.

THE FOLLOWING VARIABLES ARE USED IN SUBROUTINE SOIL2R

YA	ABSOLUTE VALUE OF LATERAL SOIL DEFLECTION
P1	SOIL RESISTANCE CALCULATED ON A P-Y CURVE
EST	SOIL MODULUS CALCULATED FROM A P-Y CURVE

APPENDIX D

LISTING OF DECK FOR BENT1

```
      PROGRAM BENT1(INPUT,OUTPUT)
      DIMENSION  ANUM(20),DISTA(20),DISTB(20),THETA(20),POTT(20),
     1           KS(20),KA(20),NN(20),HH(20),DPS(20),NDEI(20),TC(
     2           20),FDBET(20),E(20),RRI(20,5),XX1(20,5),XX2(20,5
     3           ),ZZZ(5,25),SSS(5,25),NP(5,20),XS(5,20),YC(5,20,
     4           25),PC(5,20,25),II(5),NC(5),FJY(20),FJM(20),FJX(
     5           20),AA(20),BB(20),CC(20),DD(20),EE(20),ES(105),Y
     6           (105)
      COMMON ES,Y,YC,PC,DPS,RRI,XX1,XX2,HH,NN,FDBET,XS,NC,NP
C**** BEGIN READ AND PRINT INPUT DATA ****************************
  100 READ 710 , (ANUM(I) , I=1,20)
  710     FORMAT (20A4)
      READ 711 , PV,PH,TM,TOL,KNPL,KOSC
  711     FORMAT (4E10.4,2I5)
               IF(KNPL) 9999,9999,110
  110 PRINT 712 , (ANUM(I),I=1,20)
  712     FORMAT (1H1,20A4)
      PRINT 713
  713     FORMAT ( //,5X,27H     LIST OF INPUT DATA ---///
     1             4X,67H      PV              PH              TM
     2 TOL     KNPL KOSC )
      PRINT 714,PV,PH,TM,TOL,KNPL,KOSC
  714     FORMAT(4E15.4,I3,I5)
      PRINT 715
  715     FORMAT (//,5X,43H   CONTROL DATA FOR PILES AT EACH LOCA
     1TION        5X,80H PILE NO.   DISTA           DISTB
     2BATTER       POTT      KS    KA    )
                   DO 120 K=1,KNPL
      READ 716,DISTA(K),DISTB(K),THETA(K),POTT(K),KS(K),KA(K)
      PRINT 717,K,DISTA(K),DISTB(K),THETA(K),POTT(K),KS(K),KA(K)
  716     FORMAT (4E10.4,2I5)
  717     FORMAT (5X,I5,1E15.4,3E12.4,I5,I4)
  120 CONTINUE
      PRINT 718
  718     FORMAT(//,10X,76H PILE NO.  NN         HH            DPS
     1NDEI  CONNECTION       FDBET  )
                   DO 150 I=1,KNPL
      READ 719,NN(I),HH(I),DPS(I),NDEI(I),TC(I),FDBET(I),E(I)
      PRINT 720,I,NN(I),HH(I),DPS(I),NDEI(I),TC(I),FDBET(I)
  719     FORMAT(5X,I5,2E10.5,5X,I5,7X,A3,2E10.5)
  720     FORMAT (4X,I5,2X,I5,2E15.5,I5,7X,A3,3X,E15.5 )
               NDST=NDEI(I)
                   DO 150 J=1,NDST
      READ 711,RRI(I,J),XX1(I,J),XX2(I,J)
  150 CONTINUE
      PRINT 721
  721     FORMAT(//,20X,43H      RRI           XX1           XX2)
                   DO 155 M=1,KNPL
      PRINT 741,M
  741     FORMAT (5X,7HPILE NO,I5)
               NEI=NDEI(M)
                   DO 155 N=1,NEI
      PRINT 722,RRI(M,N),XX1(M,N),XX2(M,N)
  722     FORMAT(20X,3E15.5)
  155 CONTINUE
```

```
      READ 723,NKA,NKS,KOK
      PRINT 724
  723     FORMAT(3(5X,I5))
  724     FORMAT(///,9X,28H AXIAL LOAD SETTLEMENT DATA //)
                    DO 160 L=1,NKA
      READ 723,IDEN,IO
      PRINT 725,IDEN
  725     FORMAT(9X,12H IDENTIFIER,I5,26H     ZZZ              SSS)
               II(IDEN)=IO
                    DO 160 LL=1,IO
      READ 711,ZZZ(IDEN,LL),SSS(IDEN,LL)
  160 PRINT 726,ZZZ(IDEN,LL),SSS(IDEN,LL)
  726     FORMAT(26X,2E15.5)
               IF(KOK)126,126,151
  126 PRINT 727
  727     FORMAT(//,9X,15H  P-Y CURVES   //)
                    DO 130 K=1,NKS
      READ 723,IDPY,KNC
      PRINT 728,IDPY,KNC
  728     FORMAT(9X,15H SET IDENTIFIER I5,18H NO. CURVES IN SET
     1I5,//)
               NC(IDPY)=KNC
                    DO 130 I=1,KNC
      READ 719,NP(IDPY,I),XS(IDPY,I)
      PRINT 729
  729     FORMAT(//,9X,30H     CURVE     NP        XS   )
      PRINT 730,I,NP(IDPY,I),XS(IDPY,I)
  730     FORMAT(12X,I5,4X,I5,E15.5)
               NT=NP(IDPY,I)
      PRINT 731
  731     FORMAT(//,15X,20H YC            PC   )
                    DO 130 L=1,NT
      READ 711,YC(IDPY,I,L),PC(IDPY,I,L)
      PRINT 732,YC(IDPY,I,L),PC(IDPY,I,L)
  732     FORMAT(7X,2E15.5)
  130 CONTINUE
               GO TO 152
C**** SUBROUTINE MAKE GENERATES P-Y CURVES FROM SOIL PROPERTIES *
  151 CALL MAKE(NP,NC,YC,PC,XS)
  152 CONTINUE
C**** SET INDICIES FOR INITIAL FJY,FJX,AND FJM ESTIMATION *******
  300          KFLAG=0
               KEY=0
               KSW=0
               ITER=0
               DV=0.0
               DH=0.0
               ALPHA=0.0
      PRINT 733
  733     FORMAT(/,35H1                   ITERATION DATA   //,
     1    9X,45H     DV           DH              ALPHA          )
               GO TO 325
  310 CONTINUE
               ITER=ITER+1
C**** CHECK FOR DV,DH,AND ALPHA CLOSURE *************************
```

```
            IF(ABS(DH-DHT)-TOL)315,315,325
  315       IF(ABS(DV-DVT)-TOL)320,320,325
  320       IF(ABS(ALPHA-AT)-TOL*0.001)321,321,325
C**** SET FLAG IF CLOSURE IS OBTAINED IN ORDER TO MAKE LAST PASS
C**** THROUGH SUBROUTINE COM62 ***********************************
  321       KFLAG=1
C**** IF CLOSURE IS NOT OBTAINED THE CYCLE IS REPEATED **********
  325             DO 410 I=1,KNPL
            XT=(DH+DISTB(I)*ALPHA)*SIN(THETA(I))+(DV+DISTA(I)*
     1      ALPHA)*COS(THETA(I))
            YT=(DH+DISTB(I)*ALPHA)*COS(THETA(I))-(DV+DISTA(I)*
     1      ALPHA)*SIN(THETA(I))
C**** CHECK FOR INITIAL SPRING MODULII ESTIMATIONS **************
            IF(KSW)333,326,333
C**** SET INITIAL ASSUMPTIONS FOR STARTING ITERATION PROCEDURE **
  326       XT=1.0
            YT=1.0
            BC2=0.0
            GO TO 340
  333       PT=YT*FJY(I)
            FMT=-YT*FJM(I)
            DATA CHECK1/-PIN-/,CHECK2/-FIX-/
            IF(TC(I).NE.CHECK1) GO TO 335
  334       BC2=0.0
            GO TO 340
  335       IF(TC(I).NE.CHECK2) GO TO 337
  336       BC2=-ALPHA
            GO TO 340
  337       BC2=FDBET(I)
C**** CHECK AXIAL LOAD BEHAVIOR---CALCULATE PX AND FJX(I) *******
  340       ND=KA(I)
            IT=II(ND)
                  DO 350 J=2,IT
            IF(XT-ZZZ(ND,J))355,350,350
  350 CONTINUE
      PRINT 734,I
      PRINT 735
  734     FORMAT(//,36H     FAILURE  IN BEARING--PILE NO.   I2,/)
  735     FORMAT(35H  *****PROBLEM IS ABANDONED*****    //)
            GO TO 100
  355       IF(XT-ZZZ(ND,1))360,365,365
  360 PRINT 736,I
      PRINT 735
  736     FORMAT(//,36H     FAILURE IN PULLOUT--PILE NO.   I2,/)
            GO TO 100
  365       KKK=J-1
            PX=SSS(ND,KKK)+(SSS(ND,J)-SSS(ND,KKK))*(XT-ZZZ(ND,
               KKK))/(ZZZ(ND,J)-ZZZ(ND,KKK))
            FJX(I)=PX/XT
C**** TEST KFLAG FOR LAST CYCLE THROUGH SUBROUTINE COM62 ********
  367       IF(KFLAG)400,400,370
  370 PRINT 712,(ANUM(M),M=1,20)
      PRINT 737
  737     FORMAT(/,54H PILE NUM     DISTA,IN       DISTB,IN
```

```
     1THETA,RAD )
      PRINT 738,I,DISTA(I),DISTB(I),THETA(I)
  738     FORMAT(5X,I5,4X,3E15.5)
      PRINT 739
  739     FORMAT(/ 75H          PX,LB          XT,IN          PT,LB
     1T,IN-LB       YT,IN        )
      PRINT 740,PX,XT,PT,FMT,YT
  740     FORMAT(2X,E15.5,3E14.5,E12.5)
  400         CALL COM62 (ND,PT,YT,BC2,FJYO,FJMO,TOL,I,KEY,KFLAG,
              KSW,PX,NDEI(I),TC(I),CHECK1,CHECK2,E(I),KS(I),KA(I))
               IF(KEY)405,405,100
  405          FJM(I)=FJMO
               FJY(I)=FJYO
  410 CONTINUE
               KSW=-1
C**** IF FLAG IS SET START A NEW PROBLEM--IF FLAG IS NOT SET CALC
C**** NEW VALUES OF DV,DH,AND ALPHA AND TEST FOR CLOSURE ********
  419          IF(KFLAG)420,420,100
  420          DHT=DH
               DVT=DV
               AT=ALPHA
                    DO 430 J=1,KNPL
               AA(J)=(FJX(J)*(COS(THETA(J)))**2+FJY(J)*(SIN(THETA
                     (J)))**2)*POTT(J)
               BB(J)=((FJX(J)-FJY(J))*(SIN(THETA(J))*COS(THETA(J)
                     )))*POTT(J)
               CC(J)=(FJX(J)*(SIN(THETA(J)))**2+FJY(J)*(COS(THETA
                     (J)))**2)*POTT(J)
               DD(J)=(FJM(J)*SIN(THETA(J)))*POTT(J)
               EE(J)=(-FJM(J)*COS(THETA(J)))*POTT(J)
  430 CONTINUE
               A1=0.0
               A2=0.0
               A3=0.0
               B1=0.0
               B2=0.0
               B3=0.0
               C1=0.0
               C2=0.0
               C3=0.0
                    DO 440 I=1,KNPL
               A1 = A1 + AA(I)
               B1 = B1 + BB(I)
               C1 = C1 + ( DISTA(I) * AA(I) + DISTB(I) * BB(I) )
               B2 = B2 + CC(I)
               C2 = C2 + ( DISTA(I) * BB(I) + DISTB(I) * CC(I) )
               A3=A3+(DD(I)+(DISTA(I)*AA(I))+(DISTB(I)*BB(I)))
               B3=B3+(EE(I)+(DISTA(I)*BB(I))+(DISTB(I)*CC(I)))
               C3=C3+((DISTA(I)*DD(I))+(AA(I)*DISTA(I)**2)+(DISTB
                  (I)*EE(I))+(CC(I)*DISTB(I)**2)+(2.0*DISTA(I)*DI
                  STB(I)*BB(I)))
  440 CONTINUE
               A2=B1
               DEN=A1*(B2*C3-C2*B3)-B1*(A2*C3-C2*A3)+C1*(A2*B3-B2
                   *A3)
```

```
               ALPHA=(A1*(B2*TM-PH*B3)-B1*(A2*TM-PH*A3)+PV*(A2*B3
                    -B2*A3))/DEN
               DV=(PV*(B2*C3-C2*B3)-B1*(PH*C3-C2*TM)+C1*(PH*B3-B2
                  *TM))/DEN
               DH=(A1*(PH*C3-C2*TM)-PV*(A2*C3-C2*A3)+C1*(A2*TM-PH
                  *A3))/DEN
      PRINT 780,DV,DH,ALPHA
  780     FORMAT(13X,3E15.4,/)
C**** TEST FOR OSCILLATING SOLUTION CONTROL *********************
               IF(KOSC)310,310,445
  445          IF(ITER-5)310,310,450
  450          DV=0.5*(DV+DVT)
               DH=0.5*(DH+DHT)
               ALPHA=0.5*(ALPHA+AT)
               GO TO 310
 9999          CONTINUE
      END
C
C
C
      SUBROUTINE COM62 (ND,PT,YT,BC2,FJYO,FJMO,TOL,ITYPE,KEY,KFLAG
     1,KSW,PX,NDEI,TC,CHECK1,CHECK2,E,KS,KA)
      DIMENSION Y(105),ES(105),XS(5,20),NC(5),NP(5,20),HH(20),NN
     1          (20),DPS(20),RRI(20,5),XX1(20,5),XX2(20,5),A(105)
     2          ,B(105),C(105),FDBET(20),R(105),BMT(4),YC(5,20,25)
     3          ,PC(5,20,25)
      COMMON ES,Y,YC,PC,DPS,RRI,XX1,XX2,HH,NN,FDBET,XS,NC,NP
C**** SET INDICIES AND OTHER CONSTANTS **************************
               H=HH(ITYPE)
               N=NN(ITYPE)
               NP3=N+3
               ITER=1
               K=1
C**** CAL. INITIAL ES VALUES (ES=KX,K=1.0) AND EI=R DISTRIBUTION
C**** ALONG THE PILE (STATION 3 IS TOP OF PILE) *****************
                    DO 1051 J=3,NP3
               Y(J)=0.0
               ZJ=J-3
               IF(DPS(ITYPE)-ZJ*H)1030,1030,1025
 1025          ES(J)=0.0
               GO TO 1035
 1030          ES(J)=1.0*ZJ*H-DPS(ITYPE)
 1035          IF(XX2(ITYPE,K)-ZJ*H)1040,1050,1050
 1040          K=K+1
               IF(K-NDEI)1035,1035,1045
 1045 PRINT 1015,ITYPE
      PRINT 1017
 1015     FORMAT(// 61H   EI DISTRIBUTION DOES NOT COVER TOTAL PI
     1LE LENGTH--PILE NO I5)
 1017     FORMAT(// 30H ***PROBLEM IS ABANDONED***** /)
               KEY=1
      RETURN
 1050          R(J)=RRI(ITYPE,K)
 1051 CONTINUE
C**** CALCULATE A AND B COEFFICIENTS FOR PILE
```

```
 1052          N2=NP3-1
               N1=NP3-2
               A(NP3)=(4.0*R(N2)-2.0*PX*H**2)/(2.0*R(N2)-2.0*PX*H
     1               **2+ES(NP3)*H**4)
               B(NP3)=(2.0*R(N2))/(2.0*R(N2)-2.0*PX*H**2+ES(NP3)*
     1               H**4)
               A(N2)=(2.0*R(N1)+(2.0*R(N2)-PX*H**2)*(1.0-B(NP3)))
     1              /(R(N1)+(2.0*R(N2)-PX*H**2)*(2.0-A(NP3))+ES(
     2              N2)*H**4)
               B(N2)=R(N1)/(R(N1)+(2.0*R(N2)-PX*H**2)*(2.0-A(NP3)
     1              )+ES(N2)*H**4)
                   DO 1080 J=4,N1
               KT=NP3-J+2
               C(KT)=R(KT-1)+R(KT)*(4.0-2.0*A(KT+1))+R(KT+1)*(A(K
     1              T+1)*A(KT+2)-B(KT+2)-2.0*A(KT+1)+1.0)-PX*H**
     2              2*(2.0-A(KT+1))+ES(KT)*H**4
               A(KT)=(2.0*R(KT-1)+R(KT)*(2.0-2.0*B(KT+1))+R(KT+1)
     1              *(A(KT+2)*B(KT+1)-2.0*B(KT+1))-PX*H**2*(1.0-
     2              B(KT+1)))/C(KT)
               B(KT)=R(KT-1)/C(KT)
 1080 CONTINUE
               YTMP1=Y(3)
               YTMP2=Y(4)
               IF(TC.NE.CHECK1) GO TO 1055
 1054          IF(KSW)1070,1065,1065
 1055          IF(TC.NE.CHECK2) GO TO 1057
 1056          IF(KSW)1071,1066,1066
 1057          IF(KSW)1072,1067,1067
C**** USE BC2=YT FOR FIRST PASS (PINNED CONNECTION) ************
 1065          Y(3)=YT
               Y(4)=YT*((A(4)-2.0*B(4))/(1.0-B(4)))
               GO TO 1081
C**** USE BC2=YT FOR FIRST PASS (FIXED CONNECTION) *************
 1066          S4=2.0*H*BC2
               Y(3)=YT
               Y(4)=(A(4)*YT+B(4)*S4)/(1.0+B(4))
               GO TO 1081
C**** USE BC2=YT FOR FIRST PASS (RESTRAINED CONNECTION)*********
 1067          S5=BC2*(H/2*R(3))
               Y(3)=YT
               Y(4)=(YT*(A(4)+A(4)*S5-2.0*B(4)))/(1.0+S5+B(4)*S5-
     1             B(4))
               GO TO 1081
C**** CALCULATION OF Y3 AND Y4 WITH BC1=PT AND BC2=MT ***********
 1070          S3=2.0*PT*H**3
               G1=2.0-A(4)
               G2=1.0-B(4)
               Y(3)=S3*G2/(G1*(R(3)*(2.0*B(4)-2.0)+R(4)*(4.0*B(4)
     1             -2.0*A(5)*B(4))-2.0*PX*H**2*B(4))+G2*(R(3)*(4
     2             .0-2.0*A(4))+R(4)*(2.0*A*4)*A(5)-2.0*B(5)-4.0
     3             *A(4)+2.0)+PX*H**2*(-2.0+2.0*A(4))+ES(3)*H**4))
               Y(4)=Y(3)*(A(4)-B(4)*G1/G2)
               GO TO 1081
C**** CALCULATION OF Y3 AND Y4 WITH BC1=PT AND BC2=ST ***********
 1071          S3=2.0*PT*H**3
```

```
            S4=2.0*BC2*H
            Y(3)=(S3*(1.0+B(4))+S4*(2.0*R(4)*(2.0*B(4)-A(5)*B(
    1           4))+2.0*R(3)*(B(4)-1.0)-2.0*PX*H**2*B(4)))/(2
    2           .0*R(4)*(A(4)*A(5)-B(5)-B(4)*B(5)-2.0*A(4)+1.
    3           0+B(4))+4.0*R(3)*(1.0-A(4)+B(4))+2.0*PX*H**2*(
    4           A(4)-B(4)-1.0)+ES(3)*H**4)
            Y(4)=Y(3)*(A(4)/(1.0+B(4)))+B(4)*S4/(1.0+B(4))
            GO TO 1081
C**** CALCULATION OF Y3 AND Y4 WITH BC1=PT AND BC2=MT/ST ********
 1072       S3=2.0*PT*H**3
            S5=BC2*(H/2.0*R(3))
            Y(3)'S3*(1.0-B(4)+S5*(1.0+B(4)))/(2.0*S5*(2.0*R(3)
    1           +2.0*R(3)*B(4)-2.0*R(3)*A(4)+R(4)*A(4)*A(5)-R
    2           (4)*B(5)-R(4)*B(4)*B(5)-2.0*R(4)*A(4)+R(4)+R(
    3           4)*B(4))+2.0*R(4)*(A(4)*A(5)-2.0*A(5)*B(4)-B(
    4           5)+B(4)*B(5)-2.0*A(4)+3.0*B(4)+1.0)+2.0*PX*H*
    5           *2*(A(4)-B(4)-1.0+A(4)*S5-S5-B(4)*S5)+ES(3)*H
    6           **4*(1.0-B(4)+S5*(1.0+B(4))))
            Y(4)=Y(3)*(A(4)-((B(4)*(2.0-A(4)+A(4)*S5))/(1.0+S5
    1           -B(4)+B(4)*S5)))
C**** CALCULATE DEFLECTIONS AND TEST FOR CLOSURE
 1081       KYCNT=0
            IF(ABS(Y(3)-YTMP1)-TOL)1083,1083,1082
 1082       KYCNT=KYCNT+1
 1083       IF(ABS(Y(4)-YTMP2)-TOL)1085,1085,1084
 1084       KYCNT=KYCNT+1
 1085           DO 1090 J=5,NP3
            YTMP=Y(J)
            Y(J)=A(J)*Y(J-1)-B(J)*Y(J-2)
            IF(ABS(Y(J)-YTMP)-TOL)1090,1090,1086
 1086       KYCNT=KYCNT+1
 1090 CONTINUE
            IF(KYCNT)2021,2021,1091
 1091       IF(ABS(Y(3))-3.0*E)2010,2010,1095
C**** LIMIT TOP DEFLECTION TO 3 PILE DIAMETERS
 1095       Y(3)=3.0*E
            Y(4)=Y(3)*(A(4)/(1.0+B(4)))+B(4)*S4/(1.0+B(4))
            KSW=1
            GO TO 1081
C**** IF NO CLOSURE CALL SOIL 2R AND CALCULATE NEW ES VALUES FOR
C**** THE NEXT TRIAL ***********************************
 2010 CALL SOIL 2R (KS,KEY,H,N,NP3,ITYPE)
            IF(KEY)2015,2015,2027
 2015       ITER=ITER+1
            IF(ITER-100)2017,2017,2016
 2016 PRINT 1018,ITYPE
     PRINT 1017
 1018    FORMAT(//,51H NO CLOSURE IN COM62 AFTER 100 ITERATIONS
    1PILE NO. I2)
            KEY=1
            GO TO 2027
C**** IF CLOSURE IS OBTAINED IN COM62 CHECK FOR INITIAL FJY AND
C**** FJM ESTIMATION AND FOR THE FINAL PASS *****************
 2017       GO TO 1052
 2021       IF(KFLAG)2022,2022,2030
```

```
 2022           IF(KSW)2025,2024,2024
 2024           PT=(1.0/(2.0*H**3))*(Y(5)*R(4)+Y(4)*(R(4)*(A(5)-4.
     1             0)+2.0*PX*H**2/B(4)+2.0*R(3)*(1.0/B(4)-1.0))+Y(
     2               3)*(R(4)*(2.0-B(5))+PX*H**2*(-2.0*A(4)/B(4)+2
     3               .0*A(4)-2.0)+R(3)*(4.0-2.0*A(4)/B(4))+ES(3)*H
     4               **4))
 2025           IF(TC.NE.CHECK1) GO TO 2029
 2028           FJMO=0.0
                FJYO=PT/Y(3)
                GO TO 2031
 2029           FJYO=PT/Y(3)
                TMOM=(R(3)/H**2)*(Y(3)*(A(4)/B(4)-2.0)+Y(4)*(1.0-1
     1               .0/B(4)))
                FJMO=-TMOM/Y(3)
 2031           IF(KSW)2027,2027,2026
 2026           KSW=-1
 2027 RETURN
C**** IF THE FLAG IS SET CALCULATE MOMENT AND SOIL RESISTANCE
C**** ALONG THE PILE,PRINT RESULTS,AND RETURN TO MAIN PROGRAM ***
 2030 PRINT 1002
      PRINT 1003
 1002     FORMAT (5X,18H INPUT INFORMATION /)
 1003     FORMAT(5X,78H       PT,LB          PX,LB      TC    TOP
     1DIA,IN    INC. LENGTH,IN  NO.OF INC /)
 2041 PRINT 1010,TC,E,H,N,KS,KA
 1010     FORMAT(9X,A3,2E15.4,3X,I5,5X,2I5)
      PRINT 1004
 1004     FORMAT(/,5X,71H PILE LENGTH,IN DEPTH TO SOIL  ITERATION
     1 TOL. BOUNDRY COND.2   KS   KA /)
                ZN=N
                PLGTH=ZN*H
      PRINT 1011,PLGTH,DPS(ITYPE),TOL,BC2
 1011     FORMAT(5X,4E15.4)
      PRINT 1006
 1006     FORMAT(/,30X,19H OUTPUT INFORMATION /)
C**** TEST FOR INVALID SOLUTION
                IF(KSW)2047,2046,2046
 2046 PRINT 1019
 1019     FORMAT(/ 82H INVALID SOLUTION SINCE EXCESSIVE DEFLECTION
     1 CONTROL ESTABLISHED DURING THIS CYCLE //)
 2047 PRINT 1007
 1007     FORMAT(5X,75H        X,IN           Y,IN      MOMENT,IN
     1-LB   ES,LB/IN2        P,LB/IN /)
                NP4=NP3+1
                Y(NP4)=0.0
                Y(2)=(A(4)*Y(3)-Y(4))/B(4)
                     DO 2050 J=3,NP3
                FMO=R(J)*(Y(J-1)-2.0*Y(J)+Y(J+1))/(H*H)
                RES=-ES(J)*Y(J)
                ZJ=J-3
                XIN=ZJ*H
      PRINT 1013,XIN,Y(J),FMO,ES(J),RES
 1013     FORMAT(5X,5E13.5)
 2050 CONTINUE
      RETURN
```

```
      END
C
C
C
      SUBROUTINE SOIL 2R (KS,KEY,H,N,NP3,ITYPE)
      DIMENSION Y(105),ES(105),PC(5,20,25),YC(5,20,25),NC(5),XS(5
     1         ,20),EST(20),DPS(20),RRI(20,5),XX1(20,5),XX2(20,5
     2         ),NN(20),FDBET(20),NP(5,20)HH(20)
      COMMON ES,Y,YC,PC,DPS,RRI,XX1,XX2,HH,NN,FDBET,XS,NC,NP
               K=2
                    DO 3090 J=3,NP3
               ZJ=J-3
               Z=ZJ*H-DPS(ITYPE)
               IF(Z)3010,3015,3015
 3010          ES(J)=0.0
               GO TO 3090
C**** LOCATE P-Y CURVES ABOVE AND BELOW GIVEN DEPTH
 3015          IF(XS(KS,K)-Z)3020,3027,3030
 3020          K=K+1
               IF(K-NC(KS))3015,3015,3025
 3025 PRINT 3000
      PRINT 3001
 3000     FORMAT( // 52H    P-Y CURVES DO NOT EXTEND THE LENGTH
     1OF THE PILE      )
 3001 FORMAT( /  35H     *****PROBLEM IS ABANDONED***** / )
               KEY=1
 3026 RETURN
 3027          M=K
               GO TO 3035
 3030          M=K-1
 3035          YA=ABS(Y(J))
               IF(YA-1.0E-10)3036,3037,3037
 3036          YA=1.0E-10
C**** LOCATE POINTS BEHIND AND AHEAD OF YA ON EACH P-Y CURVE AND
C**** COMPUTE ES ON EACH CURVE BY LINEAR INTERPOLATION **********
 3037               DO 3070 I=M,K
               L=2
 3040          IF(YC(KS,I,L)-YA)3045,3055,3060
 3045          L=L+1
               IF(L-NP(KS,I))3040,3040,3050
 3050          P1=PC(KS,I,L-1)
               GO TO 3065
 3055          P1=PC(KS,I,L)
               GO TO 3065
 3060          P1=PC(KS,I,L)-(PC(KS,I,L)-PC(KS,I,L-1))*(YC(KS,I,L
     1            )-YA)/(YC(KS,I,L)-YC(KS,I,L-1))
 3065          EST(I)=P1/YA
 3070 CONTINUE
C**** INTERPOLATE BETWEEN CURVES FOR CORRECT ES VALUE
               IF(K-M)3075,3075,3080
 3075          ES(J)=EST(K)
               GO TO 3090
 3080          ES(J)=(EST(K)-(EST(K)-EST(M))*(XS(KS,K)-Z)/(XS(KS,
     1                  K)-XS(KS,M)))
 3090 CONTINUE
```

```
      RETURN
      END


      SUBROUTINE MAKE (IPOINT,NC,YC,PC,DTC)
      DIMENSION TSOIL(10),GAMMA(10),PHI(10),DIS1(10),DIS2(10),KDE
     1          NSE(10),FKO(10),AV(10),SHEARS(10),INFO(10),ICON(1
     2          0),NCURVS(10),DIST(10,10),NPOINT(10,10),SIGD(10,1
     3          0,15),FP(10,10,15),D(5),DISD1(5),DISD2(5),DTC(5,2
     4          0),PC(5,20,25),YC(5,20,25),IPOINT(5,20),Q(10),NC(
     5          5)
   10  FORMAT (5X,I5)
   11  FORMAT (6X,A4)
   12 FORMAT (4E10.4,5X,A4)
   13  FORMAT (4E10.4,5X,I5,6X,A4)
   14  FORMAT (E10.4,5X,I5)
   15  FORMAT (2E10.4)
   16  FORMAT (5X,I5,5X,I5,5X,I5)
   17  FORMAT (3E10.4)
   18  FORMAT (E10.4)
   19  FORMAT(//,5X,26H INPUT OF SOIL PARAMETERS ///)
   20  FORMAT (5X,18H SOIL PROFILE NO. I5,16H    STRATUM NO. I5,1
      5H      TYPE SOIL A4//)
   21  FORMAT ( 75H  UNIT WEIGHT   ANGLE OF FRIC.  TOP DEPTH   B
      1OTTOM DEPTH       DENSITY      /)
   22 FORMAT (4E15.4,5X,A4)
   23  FORMAT ( 75H UNIT WEIGHT     COHESION        TOP DEPTH   B
     1OTTOM DEPTH    CONSISTENCY     )
   24  FORMAT  (1X,4E14.4,5X,A4,/)
   25  FORMAT (5X,31H STRESS STRAIN CURVES FOR CLAY///)
   26  FORMAT (11H CURVE NO. I2,16H DEPTH TO CURVE E10.4//)
   27  FORMAT  (25H  STRESS         STRAIN  //)
   28 FORMAT (5X,E10.4,5X,E10.4)
   29  FORMAT   (1H1)
   30  FORMAT (5X,36H                        P-Y CURVES )
   31  FORMAT (20H SET IDENTIFIER NO. I5,30H     NUMBER OF CURVES
     1 IN SET I5///)
   32  FORMAT (//,15X,31H DIAMETER DISTRIBUTION FOR PILE/)
   33  FORMAT (38H DIAMETER       TOP DIS         BOT DIS    )
   34  FORMAT (11X,E10.4,5X,E10.4,5X,E10.4,//)
   35  FORMAT  (//,11H CURVE NO. I5,16H DEPTH TO CURVE E10.4,/)
   36  FORMAT   (35H SOIL REACTION         DEFLECTION  )
   37  FORMAT   (E15.4,5X,E15.4)
C**** READ INFORMATION FOR SOIL PROFILES ***********************
      PRINT 19
      READ 10 , NSOILP
      DATA TEST1/-SAND-/,TEST2/-CLAY-/,ITESTA/-DENS-/,ITESTB/-MEDM-/
      DATA ITESTC/-LOSE-/,ITESTX/-SOFT-/,ITESTZ/-STIF-/
      DO 553 ISP= 1 ,NSOILP
      READ 10 , NSTYPE
      DO 510 IST = 1 , NSTYPE
      READ 11 , TSOIL(IST)
      PRINT 20 , ISP,IST,TSOIL(IST)
      IF(TSOIL(IST).NE.TEST1) GO TO 507
```

```
  500 READ 12,GAMMA(IST),PHI(IST),DIS1(IST),DIS2(IST),KDENSE(IST)
      PRINT 21
      PRINT 22,GAMMA(IST),PHI(IST),DIS1(IST),DIS2(IST),KDENSE(IST)
      IF(KDENSE(IST).NE.ITESTA) GO TO 502
  501 FKO(IST)=0.40
      AV(IST) =1500.0
      GO TO 510
  502 IF(KDENSE(IST).NE.ITESTB) GO TO 504
  503 FKO(IST)=0.45
      AV(IST) = 600.0
      GO TO 510
  504 FKO(IST)=0.50
      AV(IST) =200.0
      GO TO 510
  507 READ 13,GAMMA(IST),SHEARS(IST),DIS1(IST),DIS2(IST),INFO(IST)
     1,ICON(IST)
      PRINT 23
      PRINT 24,GAMMA(IST),SHEAR(IST),DIS1(IST),DIS2(IST)ICON(IST)
      IF(INFO(IST)) 510,510,508
  508 READ 10 , NCURVS(IST)
      PRINT 25
      NCUR= NCURVS(IST)
      DO 509 JJ=1,NCUR
      READ 14 , DIST(IST,JJ), NPOINT(IST,JJ)
      PRINT 26 , JJ, DIST(IST,JJ)
      PRINT 27
      NPZ = NPOINT(IST,JJ)
      DO 509 JK=1,NPZ
      READ 15, SIGD(IST,JJ,JK),FP(IST,JJ,JK)
      PRINT 28 , SIGD(IST,JJ,JK),FP(IST,JJ,JK)
  509 CONTINUE
  510 CONTINUE
C**** READ PILE DATA FOR USE IN GENERATION OF P-Y CURVRS ********
      READ 10 , NPISP
      DO 553 JP= 1 , NPISP
      PRINT 29
      PRINT 30
      READ 16 , KS , NOC , NDD
               NC(KS)=NOC
      PRINT 32
      PRINT 33
      DO 511  JD= 1,NDD
      READ 17 , D(JD) , DISD1(JD) , DISD2(JD)
  511 PRINT 34, D(JD),DISD1(JD),DISD2(JD)
      PRINT 31,KS,NOC
      DO 553 IJK= 1,NOC
      READ 18 , DTC(KS,IJK)
      PRINT 35, IJK , DTC(KS,IJK)
      PRINT 36
      DO 512 IFS= 1,NSTYPE
      IF(DIS2(IFS)-DTC(KS,IJK)) 512,513,513
  512 CONTINUE
  513 IF(TSOIL(IFS).NE.TEST1) GO TO 528
C**** GENERATION OF P-Y CURVES IN SAND *************************
  514 IF(IFS-1) 517 , 517 , 515
```

```
  515 SWGAM= 0.0
      SDIS = 0.0
      DO 516 III= 1,IFS
      WGAM = GAMMA(III)*(DIS2(III)-DIS1(III))
      SWGAM =SWGAM + WGAM
  516 SDIS = SDIS + (DIS2(III)-DIS1(III))
      AGAM = SWGAM/SDIS
      GO TO 518
  517 AGAM = GAMMA(IFS)
  518 DO 519 IPT= 1,NDD
      IF(DISD2(IPT)-DTC(KS,IJK)) 519 , 520 , 520
  519 CONTINUE
  520 DIA= D(IPT)
      ALPHA= PHI(IFS)/2.0
      ES= (AV(IFS)*AGAM*DTC(KS,IJK))/1.35
      IF(ES) 596,596,595
  596 PC(KS,IJK,2)=0.0
      YC(KS,IJK,2)=1.0
      GO TO 597
  595 C2=COS(ALPHA)
      C3= TAN(PHI(IFS))
      C4= TAN(ALPHA)
      C5= TAN(0.78539+PHI(IFS)/2.0)
      C6=C5**2
      C7= SIN(0.78539+PHI(IFS)/2.0)
      C8= TAN(0.78539-PHI(IFS)/2.0)
      C9= C8**2
      A1= AGAM*DIA*(C5/C8-C9)
      A2= AGAM*(C6*C4/C8+FKO(IFS)*C7*C3/(C2*C8)+FKO(IFS)*C5*C3*C7
     1    -FKO(IFS)*C5*C4)
      A3= AGAM*C9*DIA*(C6**4-1.0)+FKO(IFS)*DIA*AGAM*C3*C6**2
      PUW= A1*DTC(KS,IJK)+A2*DTC(KS,IJK)**2
      PUF= A3*DTC(KS,IJK)
      IF(PUW-PUF)525,526,526
  525 PC(KS,IJK,2) = PUW
      GO TO 527
  526 PC(KS,IJK,2) = PUF
  527 YC(KS,IJK,2) = PC(KS,IJK,2)/ES
  597 YC(KS,IJK,1)=0.0
      PC(KS,IJK,1) = 0.0
      YC(KS,IJK,3) = 10.0*DIA
      PC(KS,IJK,3) = PC(KS,IJK,2)
      IPOINT(KS,IJK) = 3
      DO 560 LZ = 1,3
  560 PRINT 37 , PC(KS,IJK,LZ) , YC(KS,IJK,LZ)
      GO TO 553
C**** GENERATION OF P-Y CURVES IN CLAY ***************************
  528 IF(INFO(IFS)) 529,529,548
C**** GENERATION OF P-Y CURVES FOR CLAY W/O STRESS STRAIN CURVES
C**** AVALIABLE **************************************************
  529 IF(ICON(IFS).NE.ITESTX) GO TO 531
  530 EP50=0.02
      GO TO  534
  531 IF(ICON(IFS).NE.ITESTZ) GO TO 533
  532 EP50=0.005
```

```
      GO TO  534
  533 EP50=0.01
  534 IF(IFS-1) 535,535,536
  535 AGAM=GAMMA(IFS)
      GO TO  538
  536 SGAM=0.0
      SDIS=0.0
      DO 537 III=1,IFS
      GAM= GAMMA(III)*(DIS2(III)-DIS1(III))
      SGAM= SGAM+GAM
      SDIS= SDIS+(DIS2(III)-DIS1(III))
  537 CONTINUE
      AGAM= SGAM/SDIS
  538 DO 539 IPT= 1,NDD
      IF(DISD2(IPT)-DTC(KS,IJK))539,540,540
  539 CONTINUE
  540 DIA= D(IPT)
      PUW= AGAM*DIA*DTC(KS,IJK)+2.0*SHEARS(IFS)*DIA+2.83*SHEARS(I
     1      FS)*DTC(KS,IJK)
      PUF= 11.0*SHEARS(IFS)*DIA
      SIG50= SHEARS(IFS)
      A= 2.0*(ALOG10(2.0))+ALOG10(EP50)
      EP100= 10.0**A
      DIFF = EP100/10.0
      IF(PUF-PUW) 541,541,542
  541 MPOINT = 12
      PC(KS,IJK,12) = PUF
      PC(KS,IJK,11) = PUF
      YC(KS,IJK,12) = 10.0*DIA
      YC(KS,IJK,11) = EP100*DIA
      IPOINT(KS,IJK) = 12
      GO TO  546
  542 STUP = 9.0
      DO 543 ITO=1,9
      EP= STUP*DIFF
      STUP= STUP-1.0
      PSD= ALOG10(SIG50)+0.5*(ALOG10(EP)-ALOG10(EP50))
       SIGA= 10.0**PSD
      Q(ITO)= 5.5*SIGA*DIA
      IF(PUW-Q(ITO)) 543,544,545
  543 CONTINUE
      DIFF=DIFF/10.0
      STUP=9.0
      DO 561 ITO=1,9
      EP=STUP*DIFF
      STUP=STUP-1.0
      PSD=ALOG10(SIG50)+0.5*(ALOG10(EP)-ALOG10(EP50))
      SIGA=10.0**PSD
      Q(ITO)=5.5*SIGA*DIA
      IF(PUW-Q(ITO)) 561,562,562
  561 CONTINUE
  562 IPOINT(KS,IJK)=3
      PC(KS,IJK,3)=PUW
      YC(KS,IJK,3)=10.0*DIA
      PC(KS,IJK,2)=PUW
```

```
      YC(KS,IJK,2)=EP*DIA
      GO TO 546
  544 MPOINT = 12-ITO
      KZ= MPOINT-1
      PC(KS,IJK,MPOINT) = PUW
      YC(KS,IJK,MPOINT) = 10.0*DIA
      PC(KS,IJK,KZ) = PUW
      YC(KS,IJK,KZ) = EP*DIA
      IPOINT(KS,IJK)= MPOINT
      GO TO 546
  545 MPOINT = 13-ITO
      KF= MPOINT-1
      PC(KS,IJK,MPOINT) = PUW
      PC(KS,IJK,KF) = PUW
      YC(KS,IJK,MPOINT) = 10.0*DIA
      YC(KS,IJK,KF) = (DIA*DIFF*(2.0*STUP+3.0))/2.0
      IPOINT(KS,IJK)= MPOINT
  546 CONTINUE
      YC(KS,IJK,1) = 0.0
      PC(KS,IJK,1) = 0.0
      IM= IPOINT(KS,IJK)-2
      IF(IM-1) 594,594,593
  593 TIME = 1.0
      DO 547 JT = 2 , IM
      EP= DIFF*TIME
      TIME= TIME+1.0
      ABC= ALOG10(SIG50)+0.5*(ALOG10(EP)-ALOG10(EP50))
      DSIG= 10.0**ABC
      PC(KS,IJK,JT) = 5.5*DIA*DSIG
      YC(KS,IJK,JT) = DIA*EP
  547 CONTINUE
  594 CONTINUE
      IPN= IPOINT(KS,IJK)
      DO 570  LT=1,IPN
  570 PRINT 37 , PC(KS,IJK,LT) , YC(KS,IJK,LT)
      GO TO 553
C**** GENERATION OF P-Y CURVES FOR CLAY FROM STRESS STRAIN CURVES
  548 DO 549 IPT= 1,NDD
      IF(DISD2(IPT)-DTC(KS,IJK)) 549,592,592
  549 CONTINUE
  592 DIA= D(IPT)
      NUG= NCURVS(IFS)
      DO 550 IFC =1,NUG
      IF(DIST(IFS,IFC)-DTC(KS,IJK))550,551,551
  550 CONTINUE
  551 CONTINUE
      PC(KS,IJK,1) = 0.0
      YC(KS,IJK,1) = 0.0
      MZ = NPOINT(IFS,IFC)
      DO 552 JT = 2,MZ
      YC(KS,IJK,JT) = DIA*FP(IFS,IFC,JT)
      PC(KS,IJK,JT) = 5.5*DIA*SIGD(IFS,IFC,JT)
  552 CONTINUE
      IE = NPOINT(IFS,IFC)+1
      YC(KS,IJK,IE) = 10.0*DIA
```

```
      IE1 = IE-1
      PC(KS,IJK,IE) = PC(KS,IJK,IE1)
      IPOINT(KS,IJK) = IE
      IPB= IPOINT(KS,IJK)
      DO 580  LX=1,IPB
  580 PRINT 37 , PC(KS,IJK,LX) , YC(KS,IJK,LX)
  553 CONTINUE
      RETURN
      END
```

APPENDIX E

CODED INPUT FOR EXAMPLE PROBLEMS

IDENTIFICATION INPUT BENT1 - EXAMPLE 1 CODED BY F.PARKER DATE 6/21/69 PAGE 1 OF 4

```
EXAMPLE 1 COPANO BAY CAUSEWAY , ARANSAS COUNTY TEXAS , STATE HIGHWAY 35
 8.440E+05 3.640E+04 1.682E+07 1.000E-03    4    0
-1.260E+02 0.000E+00-2.440E-01 1.000E+00    1    1
-9.000E+01 0.000E+00 0.000E+00 2.000E+00    1    1
 9.000E+01 0.000E+00 0.000E+00 2.000E+00    1    1
 1.260E+02 0.000E+00 2.440E-01 1.000E+00    1    1
        31 3.600E+01 1.200E+02         1       FIX           1.800E+01
 4.374E+10 0.000E+00 1.116E+03
        31 3.600E+01 1.200E+02         1       FIX           1.800E+01
 4.374E+10 0.000E+00 1.116E+03
        31 3.600E+01 1.200E+02         1       FIX           1.800E+01
 4.374E+10 0.000E+00 1.116E+03
        31 3.600E+01 1.200E+02         1       FIX           1.800E+01
 4.374E+10 0.000E+00 1.116E+03
         1         1         1
         1        15
```

IDENTIFICATION INPUT BENT1 - EXAMPLE 1 CODED BY F.PARKER DATE 6/21/69 PAGE 2 OF 4

```
-1.000E+01-3.600E+05
-6.500E-01-3.600E+05
-1.900E-01-2.800E+05
-1.600E-01-2.600E+05
-1.400E-01-2.400E+05
 0.000E+00 0.000E+00
 3.000E-02 4.000E+04
 4.000E-02 8.000E+04
 5.000E-02 1.000E+05
 6.000E-02 1.200E+05
 1.400E-01 2.400E+05
 1.600E-01 2.600E+05
 1.900E-01 2.800E+05
 6.500E-01 3.600E+05
 1.000E+10 3.600E+05
         1
```

IDENTIFICATION INPUT BENT1 - EXAMPLE 1 CODED BY F. PARKER DATE 6/21/69 PAGE 3 OF 4

```
         3
      CLAY
 0.000E+00 1.000E-03 0.000E+00 6.000E+01         0      SOFT
      CLAY
 1.740E-02 3.800E+00 6.000E+01 8.940E+02         0      SOFT
      CLAY
 1.740E-02 1.500E+01 8.940E+02 1.000E+03         0      SOFT
         1
         1         9         1
 1.800E+01 0.000E+00 1.000E+03
 0.000E+00
 6.000E+01
 6.100E+01
 9.600E+01
 1.320E+02
 1.680E+02
```

IDENTIFICATION INPUT BENT1 - EXAMPLE 1 CODED BY F. PARKER DATE 6/21/69 PAGE 4 OF 4

```
 2.040E+02
 2.400E+02
 9.960E+02
```

IDENTIFICATION INPUT BENT 1 - EXAMPLE 2 CODED BY F. PARKER DATE 7/9/69 PAGE 1 OF 3

```
EXAMPLE 2 HOUSTON SHIP CHANNEL BRIDGE , HARRIS COUNTY TEXAS , HIGHWAY I-610
 2.760E+07 1.126E+06 8.657E+08 1.000E-03    6    0
-1.500E+02 0.000E+00-1.660E-01 2.400E+01    1    1
-9.000E+01 0.000E+00-8.300E-02 2.300E+01    1    1
-3.000E+01 0.000E+00-4.200E-02 2.400E+01    1    1
 3.000E+01 0.000E+00 4.200E-02 2.400E+01    1    1
 9.000E+01 0.000E+00 8.300E-02 2.300E+01    1    1
 1.500E+02 0.000E+00 1.660E-01 2.400E+01    1    1
        33 1.600E+01 0.000E+00         1       FIX           1.800E+01
 4.374E+10 0.000E+00 5.280E+02
        33 1.600E+01 0.000E+00         1       FIX           1.800E+01
 4.374E+10 0.000E+00 5.280E+02
        33 1.600E+01 0.000E+00         1       FIX           1.800E+01
 4.374E+10 0.000E+00 5.280E+02
        33 1.600E+01 0.000E+00         1       FIX           1.800E+01
 4.374E+10 0.000E+00 5.280E+02
```

IDENTIFICATION INPUT BENT 1 - EXAMPLE 2 CODED BY F. PARKER DATE 7/9/69 PAGE 2 OF 3

```
        33 1.600E+01 0.000E+00         1       FIX           1.800E+01
 4.374E+10 0.000E+00 5.280E+02
        33 1.600E+01 0.000E+00         1       FIX           1.800E+01
 4.374E+10 0.000E+00 5.280E+02
         1         1         1
         1         5
-1.000E+01-6.500E+05
-5.000E-01-6.500E+05
 0.000E+00 0.000E+00
 5.000E-01 6.500E+05
 1.000E+01 6.500E+05
         1
         2
      SAND
 3.000E-02 6.000E-01 0.000E+00 1.560E+02     DENSE
      CLAY
```

IDENTIFICATION INPUT BENT1- EXAMPLE 2 CODED BY F.PARKER DATE 7/9/69 PAGE 3 OF 3

```
 1.700E-02 1.400E+01 1.560E+02 5.280E+02         0      STIF
         1
         1        10         1
 1.800E+01 0.000E+00 5.280E+02
 0.000E+00
 1.200E+01
 2.400E+01
 4.800E+01
 9.600E+01
 1.440E+02
 2.280E+02
 2.290E+02
 2.400E+02
 5.280E+02
```

APPENDIX F

OUTPUT FOR EXAMPLE PROBLEMS

```
EXAMPLE 1 COPANO BAY CAUSEWAY,ARANSAS COUNTY TEXAS,US HIGHWAY 35


      LIST OF INPUT DATA ---


     PV                 PH                 TM                 TOL       KNPL  KOSC
8.4400E+05        3.6400E+04        1.6817E+07        1.0000E-03   4      0


   CONTROL DATA FOR PILES AT EACH LOCATION

PILE NO      DISTA           DISTB          BATTER          POTT          KS    KA
     1     -1.2600E+02  0.              -2.4400E-01  1.0000E+00     1     1
     2     -9.0000E+01  0.               0.          2.0000E+00     1     1
     3      9.0000E+01  0.               0.          2.0000E+00     1     1
     4      1.2600E+02  0.               2.4400E-01  1.0000E+00     1     1


PILE NO.  NN          HH                DPS      NOEI  CONNECTION FDBET
    1     31     3.60000E+01     1.20000E+02     1        FIX        -0.
    2     31     3.60000E+01     1.20000E+02     1        FIX        -0.
    3     31     3.60000E+01     1.20000E+02     1        FIX        -0.
    4     31     3.60000E+01     1.20000E+02     1        FIX        -0.


                           RRI             XX1              XX2
PILE NO     1
                      4.37400E+10     0.                 1.11600E+03
PILE NO     2
                      4.37400E+10     0.                 1.11600E+03
PILE NO     3
                      4.37400E+10     0.                 1.11600E+03
PILE NO     4
                      4.37400E+10     0.                 1.11600E+03
```

```
    AXIAL LOAD SETTLEMENT DATA

    IDENTIFIER      1          ZZZ             SSS
                         -1.00000E+01     -3.60000E+05
                         -6.50000E-01     -3.60000E+05
                         -1.90000E-01     -2.80000E+05
                         -1.60000E-01     -2.60000E+05
                         -1.40000E-01     -2.40000E+05
                          0.               0.
                          3.00000E-02      4.00000E+04
                          4.00000E-02      8.00000E+04
                          5.00000E-02      1.00000E+05
                          6.00000E-02      1.20000E+05
                          1.40000E-01      2.40000E+05
                          1.60000E-01      2.60000E+05
                          1.90000E-01      2.80000E+05
                          6.50000E-01      3.60000E+05
                          1.00000E+01      3.60000E+05

INPUT OF SOIL PARAMETERS


 SOIL PROFILE NO.      1     STRATUM NO.      1      TYPE SOIL CLAY

   GAMMA          COHESION      TOP DEPTH    BOTTEMDEPTH    CONSISTENCY
0.             1.0000E-03     0.              6.0000E+01      SOFT

 SOIL PROFILE NO.      1     STRATUM NO.      2      TYPE SOIL CLAY

   GAMMA          COHESION      TOP DEPTH    BOTTEMDEPTH    CONSISTENCY
1.7400E-02     3.8000E+00     6.0000E+01      8.9400E+02      SOFT

 SOIL PROFILE NO.      1     STRATUM NO.      3      TYPE SOIL CLAY

   GAMMA          COHESION      TOP DEPTH    BOTTEMDEPTH    CONSISTENCY
1.7400E-02     1.5000E+01     8.9400E+02      1.0000E+03      SOFT


          DIAMETER DISTRIBUTION FOR PILE

      DIAMETER        TOP DIS           BOT DIS
      1.8000E+01      0                 1.0000E+03
```

```
                               P-Y CURVES
SET IDENTIFIER NO.      1      NUMBER OF CURVES IN SET       9



CURVE NO.      1 DEPTH TO CURVE 0

SOIL REACTION          DEFLECTION
    0.                   0.
    3.6000E-02           4.3200E-02
    3.6000E-02           1.8000E+02

CURVE NO.      2 DEPTH TO CURVE 6.0000E+01

SOIL REACTION          DEFLECTION
    0.                   0.
    6.2613E-02           1.4400E-01
    8.8548E-02           2.8800E-01
    1.0845E-01           4.3200E-01
    1.2523E-01           5.7600E-01
    1.4001E-01           7.2000E-01
    1.5337E-01           8.6400E-01
    1.6566E-01           1.0080E+00
    1.7710E-01           1.1520E+00
    1.8784E-01           1.2960E+00
    1.9800E-01           1.4400E+00
    1.9800E-01           1.8000E+02

CURVE NO.      3 DEPTH TO CURVE 6.1000E+01

SOIL REACTION          DEFLECTION
    0.                   0.
    2.3793E+02           1.4400E-01
    3.3648E+02           2.8800E-01
    4.1211E+02           4.3200E-01
    4.7586E+02           5.7600E-01
    5.3203E+02           7.2000E-01
    5.8281E+02           8.6400E-01
    6.2950E+02           1.0080E+00
    6.7297E+02           1.1520E+00
    7.1379E+02           1.2960E+00
    7.5240E+02           1.4400E+00
    7.5240E+02           1.8000E+02
```

```
CURVE NO.     4 DEPTH TO CURVE 9.6000E+01

SOIL REACTION           DEFLECTION
    0.                    0.
    2.3793E+02            1.4400E-01
    3.3648E+02            2.8800E-01
    4.1211E+02            4.3200E-01
    4.7586E+02            5.7600E-01
    5.3203E+02            7.2000E-01
    5.8281E+02            8.6400E-01
    6.2950E+02            1.0080E+00
    6.7297E+02            1.1520E+00
    7.1379E+02            1.2960E+00
    7.5240E+02            1.4400E+00
    7.5240E+02            1.8000E+02

CURVE NO.     5 DEPTH TO CURVE 1.3200E+02

SOIL REACTION           DEFLECTION
    0.                    0.
    2.3793E+02            1.4400E-01
    3.3648E+02            2.8800E-01
    4.1211E+02            4.3200E-01
    4.7586E+02            5.7600E-01
    5.3203E+02            7.2000E-01
    5.8281E+02            8.6400E-01
    6.2950E+02            1.0080E+00
    6.7297E+02            1.1520E+00
    7.1379E+02            1.2960E+00
    7.5240E+02            1.4400E+00
    7.5240E+02            1.8000E+02

CURVE NO.     6 DEPTH TO CURVE 1.6800E+02

SOIL REACTION           DEFLECTION
    0.                    0.
    2.3793E+02            1.4400E-01
    3.3648E+02            2.8800E-01
    4.1211E+02            4.3200E-01
    4.7586E+02            5.7600E-01
    5.3203E+02            7.2000E-01
    5.8281E+02            8.6400E-01
    6.2950E+02            1.0080E+00
    6.7297E+02            1.1520E+00
    7.1379E+02            1.2960E+00
    7.5240E+02            1.4400E+00
    7.5240E+02            1.8000E+02
```

```
CURVE NO.     7 DEPTH TO CURVE 2.0400E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    2.3793E+02           1.4400E-01
    3.3648E+02           2.8800E-01
    4.1211E+02           4.3200E-01
    4.7586E+02           5.7600E-01
    5.3203E+02           7.2000E-01
    5.8281E+02           8.6400E-01
    6.2950E+02           1.0080E+00
    6.7297E+02           1.1520E+00
    7.1379E+02           1.2960E+00
    7.5240E+02           1.4400E+00
    7.5240E+02           1.8000E+02


CURVE NO.     8 DEPTH TO CURVE 2.4000E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    2.3793E+02           1.4400E-01
    3.3648E+02           2.8800E-01
    4.1211E+02           4.3200E-01
    4.7586E+02           5.7600E-01
    5.3203E+02           7.2000E-01
    5.8281E+02           8.6400E-01
    6.2950E+02           1.0080E+00
    6.7297E+02           1.1520E+00
    7.1379E+02           1.2960E+00
    7.5240E+02           1.4400E+00
    7.5240E+02           1.8000E+02


CURVE NO.     9 DEPTH TO CURVE 9.9600E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    9.3920E+02           1.4400E-01
    1.3282E+03           2.8800E-01
    1.6267E+03           4.3200E-01
    1.8784E+03           5.7600E-01
    2.1001E+03           7.2000E-01
    2.3006E+03           8.6400E-01
    2.4849E+03           1.0080E+00
    2.6564E+03           1.1520E+00
    2.8176E+03           1.2960E+00
    2.9700E+03           1.4400E+00
    2.9700E+03           1.8000E+02
```

```
EXAMPLE 1 COPANO BAY CAUSEWAY,ARANSAS COUNTY TEXAS,US HIGHWAY 35

 PILE NUM      DISTA,IN        DISTB,IN         THETA,RAD
   1        -1.26000E+02    0.               -2.44000E-01

    PX,LB        XT,IN           PT,LB         MT,IN-LB         YT,IN
7.87213E+04   3.96803E-02   1.73414E+03   -2.53284E+05 1.13355E-01
 INPUT INFORMATION

    TC     TOP DIA,IN    INC. LENGTH,IN NO. OF INC    KS    KA

   FIX      1.8000E+01      3.6000E+01       31          1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    1.1160E+03      1.2000E+02      1.0000E-03     -8.5355E-05

                          OUTPUT INFORMATION

      X,IN           Y,IN      MOMENT,IN-LB     ES,LB/IN         P LB/IN

  0.              1.13356E-01 -2.53286E+05  0.              -0.
  3.60000E+01     1.06531E-01 -1.90319E+05  0.              -0.
  7.20000E+01     9.40663E-02 -1.26909E+05  0.              -0.
  1.08000E+02     7.78418E-02 -6.32023E+04  0.              -0.
  1.44000E+02     5.97446E-02  6.51531E+02  5.35396E-01 -3.19871E-02
  1.80000E+02     4.16668E-02  6.44624E+04  4.34813E-01 -1.81173E-02
  2.16000E+02     2.54989E-02  1.28099E+05  1.65229E+03 -4.21316E+01
  2.52000E+02     1.31266E-02  1.36835E+05  1.65229E+03 -2.16889E+01
  2.88000E+02     4.80862E-03  1.17143E+05  1.65229E+03 -7.94523E+00
  3.24000E+02 -3.84352E-05  8.68804E+04  1.65229E+03  6.35061E-02
  3.60000E+02 -2.31125E-03  5.64976E+04  1.65229E+03  3.81886E+00
  3.96000E+02 -2.91006E-03  3.09322E+04  1.88419E+03  5.48311E+00
  4.32000E+02 -2.59236E-03  1.24008E+04  2.11609E+03  5.48568E+00
  4.68000E+02 -1.90724E-03  9.49911E+02  2.34799E+03  4.47817E+00
  5.04000E+02 -1.19396E-03 -4.69949E+03  2.57989E+03  3.08029E+00
  5.40000E+02 -6.19929E-04 -6.34589E+03  2.81179E+03  1.74311E+00
  5.76000E+02 -2.33925E-04 -5.71840E+03  3.04369E+03  7.11995E-01
  6.12000E+02 -1.73543E-05 -4.15483E+03  3.27559E+03  5.68458E-02
  6.48000E+02  7.61099E-05 -2.50790E+03  3.50749E+03 -2.66955E-01
  6.84000E+02  9.52659E-05 -1.20110E+03  3.73939E+03 -3.56237E-01
  7.20000E+02  7.88339E-05 -3.53170E+02  3.97129E+03 -3.13073E-01
  7.56000E+02  5.19377E-05  8.98372E+01  4.20319E+03 -2.18304E-01
  7.92000E+02  2.77032E-05  2.49713E+02  4.43509E+03 -1.22866E-01
  8.28000E+02  1.08677E-05  2.49771E+02  4.66699E+03 -5.07194E-02
  8.64000E+02  1.43275E-06  1.83514E+02  4.89890E+03 -7.01889E-03
  9.00000E+02 -2.56472E-06  1.07733E+02  5.13080E+03  1.31590E-02
  9.36000E+02 -3.37009E-06  4.87547E+01  5.36270E+03  1.80728E-02
  9.72000E+02 -2.73087E-06  1.30849E+01  5.59460E+03  1.52781E-02
  1.00800E+03 -1.70396E-06 -2.81491E+00  5.82650E+03  9.92812E-03
  1.04400E+03 -7.60450E-07 -5.84134E+00  6.05840E+03  4.60711E-03
  1.08000E+03  9.98285E-09 -2.88334E+00  6.29030E+03 -6.27951E-05
  1.11600E+03  6.94984E-07 -4.65745E+01  6.52220E+03 -4.53282E-03
```

```
EXAMPLE 1 COPANO BAY CAUSEWAY,ARANSAS COUNTY TEXAS,US HIGHWAY 35

 PILE NUM     DISTA,IN       DISTB,IN       THETA,RAD
   2        -9.00000E+01    0.             0.

    PX,LB       XT,IN          PT,LB       MT,IN-LB        YT,IN
 1.33444E+05   6.89627E-02   1.49078E+03  -2.18916E+05 1.00411E-01
 INPUT INFORMATION

    TC     TOP DIA,IN    INC. LENGTH,IN NO. OF INC    KS    KA

   FIX     1.8000E+01     3.6000E+01      31           1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    1.1160E+03     1.2000E+02     1.0000E-03    -8.5355E-05

                            OUTPUT INFORMATION

     X,IN           Y,IN      MOMENT,IN-LB    ES,LB/IN         P LB/IN

  0.            1.00405E-01 -2.18910E+05  0.             -0.
  3.60000E+01   9.40888E-02 -1.64399E+05  0.             -0.
  7.20000E+01   8.29018E-02 -1.09238E+05  0.             -0.
  1.08000E+02   6.84781E-02 -5.36455E+04  0.             -0.
  1.44000E+02   5.24649E-02  2.15953E+03  5.85543E-01 -3.07205E-02
  1.80000E+02   3.65157E-02  5.79162E+04  4.34813E-01 -1.58775E-02
  2.16000E+02   2.22826E-02  1.13423E+05  1.65229E+03 -3.68173E+01
  2.52000E+02   1.14101E-02  1.20767E+05  1.65229E+03 -1.88528E+01
  2.88000E+02   4.11592E-03  1.03199E+05  1.65229E+03 -6.80069E+00
  3.24000E+02  -1.20516E-04  7.64103E+04  1.65229E+03  1.99127E-01
  3.60000E+02  -2.09294E-03  4.95771E+04  1.65229E+03  3.45815E+00
  3.96000E+02  -2.59642E-03  2.70297E+04  1.88419E+03  4.89215E+00
  4.32000E+02  -2.29901E-03  1.07157E+04  2.11609E+03  4.86492E+00
  4.68000E+02  -1.68411E-03  6.64258E+02  2.34799E+03  3.95427E+00
  5.04000E+02  -1.04952E-03 -4.26510E+03  2.57989E+03  2.70764E+00
  5.40000E+02  -5.41300E-04 -5.66849E+03  2.81179E+03  1.52202E+00
  5.76000E+02  -2.01038E-04 -5.07693E+03  3.04369E+03  6.11899E-01
  6.12000E+02  -1.12047E-05 -3.67227E+03  3.27559E+03  3.67022E-02
  6.48000E+02   6.98209E-05 -2.20553E+03  3.50749E+03 -2.44896E-01
  6.84000E+02   8.54975E-05 -1.04745E+03  3.73939E+03 -3.19709E-01
  7.20000E+02   7.01384E-05 -2.99578E+02  3.97129E+03 -2.78540E-01
  7.56000E+02   4.59029E-05  8.84938E+01  4.20319E+03 -1.92939E-01
  7.92000E+02   2.42895E-05  2.26167E+02  4.43509E+03 -1.07726E-01
  8.28000E+02   9.37730E-06  2.23333E+02  4.66699E+03 -4.37638E-02
  8.64000E+02   1.08239E-06  1.62898E+02  4.89890E+03 -5.30252E-03
  9.00000E+02  -2.38590E-06  9.49472E+01  5.13080E+03  1.22416E-02
  9.36000E+02  -3.04095E-06  4.24858E+01  5.36270E+03  1.63077E-02
  9.72000E+02  -2.43716E-06  1.09911E+01  5.59460E+03  1.36349E-02
  1.00800E+03  -1.50770E-06 -2.87609E+00  5.82650E+03  8.78463E-03
  1.04400E+03  -6.63465E-07 -5.34707E+00  6.05840E+03  4.01954E-03
  1.08000E+03   2.23410E-08 -2.58758E+00  6.29030E+03 -1.40532E-04
  1.11600E+03   6.31478E-07 -4.18708E+01  6.52220E+03 -4.11863E-03
```

```
EXAMPLE 1 COPANO BAY CAUSEWAY,ARANSAS COUNTY TEXAS,US HIGHWAY 35

 PILE NUM      DISTA,IN       DISTB,IN        THETA,RAD
    3         9.00000E+01    0.               0.

    PX,LB        XT,IN          PT,LB         MT,IN-LB        YT,IN
 1.56490E+05   8.43266E-02   1.48246E+03  -2.18831E+05 1.00411E-01
 INPUT INFORMATION

    TC     TOP DIA,IN    INC. LENGTH,IN NO. OF INC    KS    KA

   FIX     1.8000E+01     3.6000E+01      31           1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    1.1160E+03      1.2000E+02      1.0000E-03    -8.5355E-05

                               OUTPUT INFORMATION

      X,IN            Y,IN     MOMENT,IN-LB     ES,LB/IN          P LB/IN

  0.             1.00399E-01 -2.18824E+05  0.             -0.
  3.60000E+01   9.40848E-02 -1.64467E+05  0.             -0.
  7.20000E+01   8.28971E-02 -1.09348E+05  0.             -0.
  1.08000E+02   6.84695E-02 -5.37215E+04  0.             -0.
  1.44000E+02   5.24501E-02  2.15391E+03  5.85659E-01 -3.07179E-02
  1.80000E+02   3.64945E-02  5.79795E+04  4.34813E-01 -1.58683E-02
  2.16000E+02   2.22568E-02  1.13516E+05  1.65229E+03 -3.67747E+01
  2.52000E+02   1.13826E-02  1.20866E+05  1.65229E+03 -1.88073E+01
  2.88000E+02   4.08953E-03  1.03281E+05  1.65229E+03 -6.75709E+00
  3.24000E+02 -1.43336E-04  7.64600E+04  1.65229E+03  2.36833E-01
  3.60000E+02 -2.11072E-03  4.95915E+04  1.65229E+03  3.48752E+00
  3.96000E+02 -2.60872E-03  2.70130E+04  1.88419E+03  4.91533E+00
  4.32000E+02 -2.30634E-03  1.06794E+04  2.11609E+03  4.88043E+00
  4.68000E+02 -1.68753E-03  6.21345E+02  2.34799E+03  3.96231E+00
  5.04000E+02 -1.05032E-03 -4.30443E+03  2.57989E+03  2.70970E+00
  5.40000E+02 -5.40637E-04 -5.69847E+03  2.81179E+03  1.52016E+00
  5.76000E+02 -1.99802E-04 -5.09596E+03  3.04369E+03  6.08135E-01
  6.12000E+02 -9.95769E-06 -3.68168E+03  3.27559E+03  3.26173E-02
  6.48000E+02  7.07998E-05 -2.20805E+03  3.50749E+03 -2.48330E-01
  6.84000E+02  8.61335E-05 -1.04602E+03  3.73939E+03 -3.22087E-01
  7.20000E+02  7.04739E-05 -2.96571E+02  3.97129E+03 -2.79873E-01
  7.56000E+02  4.60270E-05  9.15413E+01  4.20319E+03 -1.93461E-01
  7.92000E+02  2.42925E-05  2.28505E+02  4.43509E+03 -1.07739E-01
  8.28000E+02  9.32845E-06  2.24778E+02  4.66699E+03 -4.35358E-02
  8.64000E+02  1.02450E-06  1.63587E+02  4.89890E+03 -5.01893E-03
  9.00000E+02 -2.43243E-06  9.51325E+01  5.13080E+03  1.24803E-02
  9.36000E+02 -3.07062E-06  4.24116E+01  5.36270E+03  1.64668E-02
  9.72000E+02 -2.45217E-06  1.08351E+01  5.59460E+03  1.37189E-02
  1.00800E+03 -1.51269E-06 -3.01202E+00  5.82650E+03  8.81366E-03
  1.04400E+03 -6.62445E-07 -5.42263E+00  6.05840E+03  4.01335E-03
  1.08000E+03  2.71272E-08 -2.60678E+00  6.29030E+03 -1.70638E-04
  1.11600E+03  6.39461E-07 -4.22481E+01  6.52220E+03 -4.17069E-03
```

```
EXAMPLE 1 COPANO BAY CAUSEWAY,ARANSAS COUNTY TEXAS,US HIGHWAY 35

 PILE NUM      DISTA,IN        DISTB,IN        THETA,RAD
    4        1.26000E+02    0.               2.44000E-01

    PX,LB        XT,IN          PT,LB        MT,IN-LB         YT,IN
 1.93603E+05   1.09068E-01   1.06245E+03   -1.55201E+05 7.63223E-02
 INPUT INFORMATION

    TC     TOP DIA,IN    INC. LENGTH,IN NO. OF INC   KS   KA

   FIX     1.8000E+01     3.6000E+01      31          1    1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    1.1160E+03     1.2000E+02     1.0000E-03    -8.5355E-05

                              OUTPUT INFORMATION

      X,IN          Y,IN     MOMENT,IN-LB    ES,LB/IN        P LB/IN

  0.             7.62891E-02 -1.55206E+05  0.            -0.
  3.60000E+01  7.09170E-02 -1.15918E+05  0.            -0.
  7.20000E+01  6.21102E-02 -7.59645E+04  0.            -0.
  1.08000E+02  5.10527E-02 -3.55755E+04  0.            -0.
  1.44000E+02  3.89411E-02  5.01770E+03  6.73925E-01 -2.62434E-02
  1.80000E+02  2.69781E-02  4.55481E+04  4.34813E-01 -1.17304E-02
  2.16000E+02  1.63647E-02  8.58019E+04  1.65229E+03 -2.70393E+01
  2.52000E+02  8.29365E-03  9.05207E+04  1.65229E+03 -1.37035E+01
  2.88000E+02  2.90464E-03  7.69604E+04  1.65229E+03 -4.79931E+00
  3.24000E+02 -2.04055E-04  5.67387E+04  1.65229E+03  3.37158E-01
  3.60000E+02 -1.63161E-03  3.66285E+04  1.65229E+03  2.69589E+00
  3.96000E+02 -1.97387E-03  1.98021E+04  1.88419E+03  3.71914E+00
  4.32000E+02 -1.72940E-03  7.68209E+03  2.11609E+03  3.65956E+00
  4.68000E+02 -1.25731E-03  2.60804E+02  2.34799E+03  2.95216E+00
  5.04000E+02 -7.77498E-04 -3.33599E+03  2.57989E+03  2.00586E+00
  5.40000E+02 -3.96529E-04 -4.31404E+03  2.81179E+03  1.11496E+00
  5.76000E+02 -1.43383E-04 -3.82237E+03  3.04369E+03  4.36413E-01
  6.12000E+02 -3.49209E-06 -2.74318E+03  3.27559E+03  1.14386E-02
  6.48000E+02  5.51189E-05 -1.63344E+03  3.50749E+03 -1.93329E-01
  6.84000E+02  6.53318E-05 -7.64871E+02  3.73939E+03 -2.44301E-01
  7.20000E+02  5.28818E-05 -2.08533E+02  3.97129E+03 -2.10009E-01
  7.56000E+02  3.42531E-05  7.68293E+01  4.20319E+03 -1.43972E-01
  7.92000E+02  1.79008E-05  1.75163E+02  4.43509E+03 -7.93917E-02
  8.28000E+02  6.73851E-06  1.69600E+02  4.66699E+03 -3.14486E-02
  8.64000E+02  6.01402E-07  1.22306E+02  4.89890E+03 -2.94621E-03
  9.00000E+02 -1.91182E-06  7.04930E+01  5.13080E+03  9.80915E-03
  9.36000E+02 -2.33636E-06  3.09880E+01  5.36270E+03  1.25292E-02
  9.72000E+02 -1.84273E-06  7.54313E+00  5.59460E+03  1.03094E-02
  1.00800E+03 -1.12561E-06 -2.58413E+00  5.82650E+03  6.55836E-03
  1.04400E+03 -4.85053E-07 -4.19692E+00  6.05840E+03  2.93864E-03
  1.08000E+03  3.11518E-08 -1.97715E+00  6.29030E+03 -1.95954E-04
  1.11600E+03  4.88774E-07 -3.19409E+01  6.52220E+03 -3.18788E-03
```

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EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610


     LIST OF INPUT DATA ---


     PV                PH                TM              TOL        KNPL KOSC
2.7600E+07       1.1260E+06       8.6568E+08       1.0000E-03  6     0


   CONTROL DATA FOR PILES AT EACH LOCATION

PILE NO     DISTA          DISTB          BATTER          POTT          KS   KA
    1     -1.5000E+02  0.              -1.6600E-01  2.4000E+01     1    1
    2     -9.0000E+01  0.              -8.3000E-02  2.3000E+01     1    1
    3     -3.0000E+01  0.              -4.2000E-02  2.4000E+01     1    1
    4      3.0000E+01  0.               4.2000E-02  2.4000E+01     1    1
    5      9.0000E+01  0.               8.3000E-02  2.3000E+01     1    1
    6      1.5000E+02  0.               1.6600E-01  2.4000E+01     1    1


PILE NO.  NN        HH                   DPS    NDEI   CONNECTION FDBET
   1      33     1.60000E+01     0.                 1        FIX      -0.
   2      33     1.60000E+01     0.                 1        FIX      -0.
   3      33     1.60000E+01     0.                 1        FIX      -0.
   4      33     1.60000E+01     0.                 1        FIX      -0.
   5      33     1.60000E+01     0.                 1        FIX      -0.
   6      33     1.60000E+01     0.                 1        FIX      -0.


                           RRI             XX1             XX2
PILE NO    1
                       4.37400E+10     0.              5.28000E+02
PILE NO    2
                       4.37400E+10     0.              5.28000E+02
PILE NO    3
                       4.37400E+10     0.              5.28000E+02
PILE NO    4
                       4.37400E+10     0.              5.28000E+02
PILE NO    5
                       4.37400E+10     0.              5.28000E+02
PILE NO    6
                       4.37400E+10     0.              5.28000E+02
```

```
    AXIAL LOAD SETTLEMENT DATA


    IDENTIFIER      1          ZZZ              SSS
                          -1.00000E+01   -6.00000E+05
                          -5.00000E-01   -6.00000E+05
                           0.              0.
                           5.00000E-01    6.50000E+05
                           1.00000E+01    6.50000E+05


 INPUT OF SOIL PARAMETERS


 SOIL PROFILE NO.      1     STRATUM NO.      1      TYPE SOIL SAND

 GAMMA      ANGLE OF FRIC.  TOP DEPTH     BOTTEM DEPTH       DENSITY
3.0000E-02      6.0000E-01     0.              1.5600E+02    DENSE

 SOIL PROFILE NO.      1     STRATUM NO.      2      TYPE SOIL CLAY

   GAMMA         COHESION      TOP DEPTH   BOTTEMDEPTH   CONSISTENCY
1.7000E-02    1.4000E+01    1.5600E+02    5.2800E+02      STIF


          DIAMETER DISTRIBUTION FOR PILE

     DIAMETER        TOP DIS          BOT DIS
     1.8000E+01      0                5.2800E+02
```

```
                                         P-Y CURVES
SET IDENTIFIER NO.      1      NUMBER OF CURVES IN SET      10




CURVE NO.      1 DEPTH TO CURVE 0

SOIL REACTION          DEFLECTION
    0.                   0.
    0.                   1.0000E+00
    0.                   1.8000E+02


CURVE NO.      2 DEPTH TO CURVE 1.2000E+01

SOIL REACTION          DEFLECTION
    0.                   0.
    3.3634E+01           8.4085E-02
    3.3634E+01           1.8000E+02


CURVE NO.      3 DEPTH TO CURVE 2.4000E+01

SOIL REACTION          DEFLECTION
    0.                   0.
    9.1565E+01           1.1446E-01
    9.1565E+01           1.8000E+02


CURVE NO.      4 DEPTH TO CURVE 4.8000E+01

SOIL REACTION          DEFLECTION
    0.                   0.
    2.8032E+02           1.7520E-01
    2.8032E+02           1.8000E+02


CURVE NO.      5 DEPTH TO CURVE 9.6000E+01

SOIL REACTION          DEFLECTION
    0.                   0.
    9.4939E+02           2.9668E-01
    9.4939E+02           1.8000E+02


CURVE NO.      6 DEPTH TO CURVE 1.4400E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    2.0072E+03           4.1817E-01
    2.0072E+03           1.8000E+02
```

```
CURVE NO.     7 DEPTH TO CURVE 2.2800E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    8.7658E+02           3.6000E-02
    1.2397E+03           7.2000E-02
    1.5183E+03           1.0800E-01
    1.7532E+03           1.4400E-01
    1.9601E+03           1.8000E-01
    2.1472E+03           2.1600E-01
    2.3192E+03           2.5200E-01
    2.4794E+03           2.8800E-01
    2.6298E+03           3.2400E-01
    2.7720E+03           3.6000E-01
    2.7720E+03           1.8000E+02

CURVE NO.     8 DEPTH TO CURVE 2.2900E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    8.7658E+02           3.6000E-02
    1.2397E+03           7.2000E-02
    1.5183E+03           1.0800E-01
    1.7532E+03           1.4400E-01
    1.9601E+03           1.8000E-01
    2.1472E+03           2.1600E-01
    2.3192E+03           2.5200E-01
    2.4794E+03           2.8800E-01
    2.6298E+03           3.2400E-01
    2.7720E+03           3.6000E-01
    2.7720E+03           1.8000E+02

CURVE NO.     9 DEPTH TO CURVE 2.4000E+02

SOIL REACTION          DEFLECTION
    0.                   0.
    8.7658E+02           3.6000E-02
    1.2397E+03           7.2000E-02
    1.5183E+03           1.0800E-01
    1.7532E+03           1.4400E-01
    1.9601E+03           1.8000E-01
    2.1472E+03           2.1600E-01
    2.3192E+03           2.5200E-01
    2.4794E+03           2.8800E-01
    2.6298E+03           3.2400E-01
    2.7720E+03           3.6000E-01
    2.7720E+03           1.8000E+02
```

```
CURVE NO.    10 DEPTH TO CURVE 5.2800E+02

SOIL REACTION         DEFLECTION
    0.                  0.
    8.7658E+02          3.6000E-02
    1.2397E+03          7.2000E-02
    1.5183E+03          1.0800E-01
    1.7532E+03          1.4400E-01
    1.9601E+03          1.8000E-01
    2.1472E+03          2.1600E-01
    2.3192E+03          2.5200E-01
    2.4794E+03          2.8800E-01
    2.6298E+03          3.2400E-01
    2.7720E+03          3.6000E-01
    2.7720E+03          1.8000E+02
```

```
EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610

PILE NUM      DISTA,IN       DISTB,IN        THETA,RAD
   1       -1.50000E+02    0.               -1.66000E-01

    PX,LB       XT,IN           PT,LB        MT,IN-LB          YT,IN
1.06315E+05   8.17810E-02   3.28731E+03  -4.59889E+04 4.73728E-02
INPUT INFORMATION

    TC     TOP DIA,IN     INC. LENGTH,IN NO. OF INC    KS    KA

   FIX      1.8000E+01      1.6000E+01       33          1     1

PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    5.2800E+02     0.              1.0000E-03    -4.1831E-04

                            OUTPUT INFORMATION

      X,IN             Y,IN     MOMENT,IN-LB     ES,LB/IN         P LB/IN

   0.             4.68923E-02 -4.88633E+04  1.81899E-12 -8.52967E-14
   1.60000E+01   4.00564E-02  4.46043E+03  5.33333E+02 -2.13634E+01
   3.20000E+01   3.32465E-02  5.23123E+04  1.06667E+03 -3.54629E+01
   4.80000E+01   2.67428E-02  9.10532E+04  1.60000E+03 -4.27885E+01
   6.40000E+01   2.07720E-02  1.18784E+05  2.13333E+03 -4.43137E+01
   8.00000E+01   1.54965E-02  1.35096E+05  2.66667E+03 -4.13239E+01
   9.60000E+01   1.10116E-02  1.40745E+05  3.20000E+03 -3.52371E+01
   1.12000E+02   7.35045E-03  1.37286E+05  3.73333E+03 -2.74417E+01
   1.28000E+02   4.49281E-03  1.26716E+05  4.26667E+03 -1.91693E+01
   1.44000E+02   2.37682E-03  1.11160E+05  4.80000E+03 -1.14087E+01
   1.60000E+02   9.11415E-04  9.26145E+04  8.52372E+03 -7.76865E+00
   1.76000E+02  -1.19363E-05  7.20225E+04  1.22474E+04  1.46189E-01
   1.92000E+02  -5.13757E-04  5.14231E+04  1.59712E+04  8.20530E+00
   2.08000E+02  -7.14610E-04  3.28922E+04  1.96949E+04  1.40742E+01
   2.24000E+02  -7.22954E-04  1.79438E+04  2.34186E+04  1.69306E+01
   2.40000E+02  -6.26276E-04  7.31855E+03  2.43495E+04  1.52495E+01
   2.56000E+02  -4.86764E-04  5.92590E+02  2.43495E+04  1.18525E+01
   2.72000E+02  -3.43784E-04 -3.09951E+03  2.43495E+04  8.37099E+00
   2.88000E+02  -2.18945E-04 -4.64670E+03  2.43495E+04  5.33121E+00
   3.04000E+02  -1.21302E-04 -4.82621E+03  2.43495E+04  2.95364E+00
   3.20000E+02  -5.19054E-05 -4.24659E+03  2.43495E+04  1.26387E+00
   3.36000E+02  -7.36313E-06 -3.34077E+03  2.43495E+04  1.79289E-01
   3.52000E+02   1.76264E-05 -2.38697E+03  2.43495E+04 -4.29194E-01
   3.68000E+02   2.86454E-05 -1.54157E+03  2.43495E+04 -6.97503E-01
   3.84000E+02   3.06421E-05 -8.73764E+02  2.43495E+04 -7.46121E-01
   4.00000E+02   2.75248E-05 -3.96423E+02  2.43495E+04 -6.70216E-01
   4.16000E+02   2.20873E-05 -9.04101E+01  2.43495E+04 -5.37817E-01
   4.32000E+02   1.61207E-05  7.79776E+01  2.43495E+04 -3.92533E-01
   4.48000E+02   1.06105E-05  1.45828E+02  2.43495E+04 -2.58361E-01
   4.64000E+02   5.95380E-06  1.47448E+02  2.43495E+04 -1.44972E-01
   4.80000E+02   2.16006E-06  1.11863E+02  2.43495E+04 -5.25964E-02
   4.96000E+02  -9.78979E-07  6.27436E+01  2.43495E+04  2.38377E-02
   5.12000E+02  -3.75079E-06  1.96877E+01  2.43495E+04  9.13300E-02
   5.28000E+02  -6.40737E-06  1.54866E+03  2.43495E+04  1.56017E-01
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EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610

 PILE NUM      DISTA,IN        DISTB,IN        THETA,RAD
    2       -9.00000E+01    0.               -8.30000E-02

     PX,LB        XT,IN           PT,LB        MT,IN-LB          YT,IN
 1.43571E+05   1.10439E-01    2.52241E+03    3.97335E+02 4.25105E-02
 INPUT INFORMATION

     TC     TOP DIA,IN     INC. LENGTH,IN NO. OF INC    KS    KA

    FIX      1.8000E+01      1.6000E+01      33           1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

     5.2800E+02      0.                 1.0000E-03    -4.1831E-04

                                   OUTPUT INFORMATION

      X,IN            Y,IN    MOMENT,IN-LB     ES,LB/IN         P LB/IN

  0.             4.21030E-02 -2.02709E+03  1.81899E-12 -7.65850E-14
  1.60000E+01  3.54041E-02  3.92933E+04  5.33333E+02 -1.88822E+01
  3.20000E+01  2.89352E-02  7.57469E+04  1.06667E+03 -3.08642E+01
  4.80000E+01  2.29096E-02  1.04236E+05  1.60000E+03 -3.66554E+01
  6.40000E+01  1.74941E-02  1.23253E+05  2.13333E+03 -3.73207E+01
  8.00000E+01  1.27999E-02  1.32612E+05  2.66667E+03 -3.41331E+01
  9.60000E+01  8.88188E-03  1.33123E+05  3.20000E+03 -2.84220E+01
  1.12000E+02  5.74299E-03  1.26245E+05  3.73333E+03 -2.14405E+01
  1.28000E+02  3.34299E-03  1.13772E+05  4.26667E+03 -1.42634E+01
  1.44000E+02  1.60887E-03  9.75526E+04  4.80000E+03 -7.72257E+00
  1.60000E+02  4.45701E-04  7.92740E+04  8.52372E+03 -3.79904E+00
  1.76000E+02 -2.53494E-04  5.99562E+04  1.22474E+04  3.10465E+00
  1.92000E+02 -6.01780E-04  4.13829E+04  1.59712E+04  9.61112E+00
  2.08000E+02 -7.07861E-04  2.52352E+04  1.96949E+04  1.39412E+01
  2.24000E+02 -6.66246E-04  1.26353E+04  2.34186E+04  1.56026E+01
  2.40000E+02 -5.50680E-04  4.01902E+03  2.43495E+04  1.34088E+01
  2.56000E+02 -4.11592E-04 -1.16799E+03  2.43495E+04  1.00221E+01
  2.72000E+02 -2.79339E-04 -3.78836E+03  2.43495E+04  6.80178E+00
  2.88000E+02 -1.69259E-04 -4.66430E+03  2.43495E+04  4.12138E+00
  3.04000E+02 -8.64781E-05 -4.48124E+03  2.43495E+04  2.10570E+00
  3.20000E+02 -2.99248E-05 -3.75536E+03  2.43495E+04  7.28655E-01
  3.36000E+02  4.64930E-06 -2.83979E+03  2.43495E+04 -1.13208E-01
  3.52000E+02  2.26028E-05 -1.95081E+03  2.43495E+04 -5.50367E-01
  3.68000E+02  2.91386E-05 -1.20108E+03  2.43495E+04 -7.09513E-01
  3.84000E+02  2.86449E-05 -6.31986E+02  2.43495E+04 -6.97489E-01
  4.00000E+02  2.44522E-05 -2.40914E+02  2.43495E+04 -5.95400E-01
  4.16000E+02  1.88495E-05 -2.06183E+00  2.43495E+04 -4.58977E-01
  4.32000E+02  1.32348E-05  1.19294E+02  2.43495E+04 -3.22261E-01
  4.48000E+02  8.31824E-06  1.58050E+02  2.43495E+04 -2.02545E-01
  4.64000E+02  4.32673E-06  1.44822E+02  2.43495E+04 -1.05354E-01
  4.80000E+02  1.18283E-06  1.04502E+02  2.43495E+04 -2.88013E-02
  4.96000E+02 -1.34944E-06  5.67213E+01  2.43495E+04  3.28583E-02
  5.12000E+02 -3.54973E-06  1.73043E+01  2.43495E+04  8.64344E-02
  5.28000E+02 -5.64875E-06  1.32378E+03  2.43495E+04  1.37544E-01
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EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610

 PILE NUM      DISTA,IN        DISTB,IN        THETA,RAD
    3        -3.00000E+01     0.              -4.20000E-02

    PX,LB        XT,IN          PT,LB         MT,IN-LB        YT,IN
 1.78315E+05   1.37165E-01   1.97946E+03   3.28630E+04 3.90018E-02
 INPUT INFORMATION

    TC     TOP DIA,IN    INC. LENGTH,IN NO. OF INC   KS   KA

   FIX     1.8000E+01     1.6000E+01      33          1    1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    5.2800E+02      0.              1.0000E-03    -4.1831E-04

                          OUTPUT INFORMATION

      X,IN          Y,IN      MOMENT,IN-LB    ES,LB/IN        P LB/IN

  0.             3.87067E-02  3.11152E+04  1.81899E-12 -7.04071E-14
  1.60000E+01  3.21048E-02  6.39638E+04  5.33333E+02 -1.71226E+01
  3.20000E+01  2.58772E-02  9.23622E+04  1.06667E+03 -2.76024E+01
  4.80000E+01  2.01902E-02  1.13598E+05  1.60000E+03 -3.23044E+01
  6.40000E+01  1.51681E-02  1.26445E+05  2.13333E+03 -3.23587E+01
  8.00000E+01  1.08861E-02  1.30877E+05  2.66667E+03 -2.90295E+01
  9.60000E+01  7.36999E-03  1.27740E+05  3.20000E+03 -2.35840E+01
  1.12000E+02  4.60156E-03  1.18433E+05  3.73333E+03 -1.71792E+01
  1.28000E+02  2.52628E-03  1.04604E+05  4.26667E+03 -1.07788E+01
  1.44000E+02  1.06323E-03  8.79068E+04  4.80000E+03 -5.10352E+00
  1.60000E+02  1.14681E-04  6.98112E+04  8.52372E+03 -9.77511E-01
  1.76000E+02 -4.25283E-04  5.13924E+04  1.22474E+04  5.20863E+00
  1.92000E+02 -6.64460E-04  3.42535E+04  1.59712E+04  1.06122E+01
  2.08000E+02 -7.03158E-04  1.97955E+04  1.96949E+04  1.38486E+01
  2.24000E+02 -6.25999E-04  8.86207E+03  2.34186E+04  1.46600E+01
  2.40000E+02 -4.96972E-04  1.67239E+03  2.43495E+04  1.21010E+01
  2.56000E+02 -3.58157E-04 -2.42117E+03  2.43495E+04  8.72096E+00
  2.72000E+02 -2.33513E-04 -4.27964E+03  2.43495E+04  5.68592E+00
  2.88000E+02 -1.33916E-04 -4.67804E+03  2.43495E+04  3.26079E+00
  3.04000E+02 -6.16985E-05 -4.23680E+03  2.43495E+04  1.50233E+00
  3.20000E+02 -1.42782E-05 -3.40655E+03  2.43495E+04  3.47667E-01
  3.36000E+02  1.32044E-05 -2.48373E+03  2.43495E+04 -3.21521E-01
  3.52000E+02  2.61503E-05 -1.64063E+03  2.43495E+04 -6.36747E-01
  3.68000E+02  2.94939E-05 -9.58832E+02  2.43495E+04 -7.18162E-01
  3.84000E+02  2.72257E-05 -4.59878E+02  2.43495E+04 -6.62932E-01
  4.00000E+02  2.22659E-05 -1.30155E+02  2.43495E+04 -5.42164E-01
  4.16000E+02  1.65444E-05  6.09099E+01  2.43495E+04 -4.02848E-01
  4.32000E+02  1.11793E-05  1.48782E+02  2.43495E+04 -2.72211E-01
  4.48000E+02  6.68507E-06  1.66813E+02  2.43495E+04 -1.62778E-01
  4.64000E+02  3.16714E-06  1.42999E+02  2.43495E+04 -7.71184E-02
  4.80000E+02  4.86142E-07  9.92927E+01  2.43495E+04 -1.18373E-02
  4.96000E+02 -1.61372E-06  5.24527E+01  2.43495E+04  3.92933E-02
  5.12000E+02 -3.40658E-06  1.56171E+01  2.43495E+04  8.29487E-02
  5.28000E+02 -5.10805E-06  1.16347E+03  2.43495E+04  1.24379E-01
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EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610

 PILE NUM      DISTA,IN        DISTB,IN         THETA,RAD
    4        3.00000E+01     0.                4.20000E-02

    PX,LB        XT,IN           PT,LB          MT,IN-LB         YT,IN
 2.14540E+05   1.65031E-01   3.28645E+02    1.22087E+05 2.63021E-02
 INPUT INFORMATION

    TC     TOP DIA,IN     INC. LENGTH,IN NO. OF INC    KS    KA

   FIX      1.8000E+01      1.6000E+01       33          1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    5.2800E+02      0.                 1.0000E-03    -4.1831E-04

                                  OUTPUT INFORMATION

      X,IN            Y,IN     MOMENT,IN-LB     ES,LB/IN          P LB/IN

   0.            2.82583E-02  1.33612E+05  1.81899E-12 -5.14015E-14
   1.60000E+01  2.19563E-02  1.40222E+05  5.33333E+02 -1.17100E+01
   3.20000E+01  1.64750E-02  1.43658E+05  1.06667E+03 -1.75733E+01
   4.80000E+01  1.18345E-02  1.42416E+05  1.60000E+03 -1.89352E+01
   6.40000E+01  8.02754E-03  1.36147E+05  2.13333E+03 -1.71254E+01
   8.00000E+01  5.01741E-03  1.25323E+05  2.66667E+03 -1.33798E+01
   9.60000E+01  2.74076E-03  1.10916E+05  3.20000E+03 -8.77044E+00
   1.12000E+02  1.11329E-03  9.41254E+04  3.73333E+03 -4.15627E+00
   1.28000E+02  3.67021E-05  7.61522E+04  4.26667E+03 -1.56595E-01
   1.44000E+02 -5.94180E-04  5.80433E+04  4.80000E+03  2.85207E+00
   1.60000E+02 -8.85349E-04  4.05916E+04  8.52372E+03  7.54647E+00
   1.76000E+02 -9.38945E-04  2.50208E+04  1.22474E+04  1.14997E+01
   1.92000E+02 -8.46100E-04  1.23626E+04  1.59712E+04  1.35132E+01
   2.08000E+02 -6.80899E-04  3.14819E+03  1.96949E+04  1.34102E+01
   2.24000E+02 -4.97273E-04 -2.63714E+03  2.34186E+04  1.16454E+01
   2.40000E+02 -3.29082E-04 -5.43792E+03  2.43495E+04  8.01299E+00
   2.56000E+02 -1.92717E-04 -6.18055E+03  2.43495E+04  4.69257E+00
   2.72000E+02 -9.25257E-05 -5.71412E+03  2.43495E+04  2.25296E+00
   2.88000E+02 -2.57777E-05 -4.66375E+03  2.43495E+04  6.27676E-01
   3.04000E+02  1.36744E-05 -3.44685E+03  2.43495E+04 -3.32965E-01
   3.20000E+02  3.29529E-05 -2.31085E+03  2.43495E+04 -8.02388E-01
   3.36000E+02  3.87065E-05 -1.37737E+03  2.43495E+04 -9.42487E-01
   3.52000E+02  3.63988E-05 -6.83430E+02  2.43495E+04 -8.86294E-01
   3.68000E+02  3.00911E-05 -2.15525E+02  2.43495E+04 -7.32704E-01
   3.84000E+02  2.25219E-05  6.50777E+01  2.43495E+04 -5.48399E-01
   4.00000E+02  1.53337E-05  2.05209E+02  2.43495E+04 -3.73369E-01
   4.16000E+02  9.34650E-06  2.49500E+02  2.43495E+04 -2.27583E-01
   4.32000E+02  4.81955E-06  2.35216E+02  2.43495E+04 -1.17354E-01
   4.48000E+02  1.66928E-06  1.90595E+02  2.43495E+04 -4.06461E-02
   4.64000E+02 -3.65492E-07  1.35329E+02  2.43495E+04  8.89956E-03
   4.80000E+02 -1.60821E-06  8.21711E+01  2.43495E+04  3.91592E-02
   4.96000E+02 -2.37000E-06  3.89349E+01  2.43495E+04  5.77085E-02
   5.12000E+02 -2.90392E-06  1.04232E+01  2.43495E+04  7.07091E-02
   5.28000E+02 -3.37683E-06  6.57764E+02  2.43495E+04  8.22242E-02
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EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610

 PILE NUM      DISTA,IN        DISTB,IN        THETA,RAD
    5         9.00000E+01     0.              8.30000E-02

     PX,LB       XT,IN          PT,LB         MT,IN-LB         YT,IN
 2.48277E+05   1.90982E-01   1.83819E+02   8.38395E+04 1.74349E-02
 INPUT INFORMATION

     TC      TOP DIA,IN     INC. LENGTH,IN NO. OF INC    KS    KA

    FIX      1.8000E+01      1.6000E+01       33          1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

     5.2800E+02      0.              1.0000E-03    -4.1831E-04

                                  OUTPUT INFORMATION

       X,IN            Y,IN      MOMENT,IN-LB     ES,LB/IN         P LB/IN

   0.             2.73692E-02  1.42080E+05  1.81899E-12 -4.97843E-14
   1.60000E+01  2.10920E-02  1.46580E+05  5.33333E+02 -1.12491E+01
   3.20000E+01  1.56727E-02  1.47986E+05  1.06667E+03 -1.67176E+01
   4.80000E+01  1.11195E-02  1.44899E+05  1.60000E+03 -1.77913E+01
   6.40000E+01  7.41443E-03  1.37046E+05  2.13333E+03 -1.58175E+01
   8.00000E+01  4.51141E-03  1.24944E+05  2.66667E+03 -1.20304E+01
   9.60000E+01  2.33967E-03  1.09581E+05  3.20000E+03 -7.48694E+00
   1.12000E+02  8.09274E-04  9.21426E+04  3.73333E+03 -3.02129E+00
   1.28000E+02 -1.81830E-04  7.37966E+04  4.26667E+03  7.75807E-01
   1.44000E+02 -7.41020E-04  5.55420E+04  4.80000E+03  3.55689E+00
   1.60000E+02 -9.75135E-04  3.81172E+04  8.52372E+03  8.31178E+00
   1.76000E+02 -9.86160E-04  2.27648E+04  1.22474E+04  1.20779E+01
   1.92000E+02 -8.63948E-04  1.04713E+04  1.59712E+04  1.37983E+01
   2.08000E+02 -6.80450E-04  1.69495E+03  1.96949E+04  1.34014E+01
   2.24000E+02 -4.87032E-04 -3.65311E+03  2.34186E+04  1.14056E+01
   2.40000E+02 -3.14994E-04 -6.07602E+03  2.43495E+04  7.66996E+00
   2.56000E+02 -1.78518E-04 -6.52660E+03  2.43495E+04  4.34684E+00
   2.72000E+02 -8.02409E-05 -5.85490E+03  2.43495E+04  1.95383E+00
   2.88000E+02 -1.62310E-05 -4.67452E+03  2.43495E+04  3.95217E-01
   3.04000E+02  2.04201E-05 -3.38616E+03  2.43495E+04 -4.97221E-01
   3.20000E+02  3.72528E-05 -2.22018E+03  2.43495E+04 -9.07089E-01
   3.36000E+02  4.10913E-05 -1.28318E+03  2.43495E+04 -1.00055E+00
   3.52000E+02  3.74197E-05 -6.00460E+02  2.43495E+04 -9.11152E-01
   3.68000E+02  3.02337E-05 -1.50122E+02  2.43495E+04 -7.36177E-01
   3.84000E+02  2.21691E-05  1.11972E+02  2.43495E+04 -5.39807E-01
   4.00000E+02  1.47598E-05  2.35713E+02  2.43495E+04 -3.59394E-01
   4.16000E+02  8.73010E-06  2.67106E+02  2.43495E+04 -2.12574E-01
   4.32000E+02  4.26371E-06  2.43693E+02  2.43495E+04 -1.03819E-01
   4.48000E+02  1.22360E-06  1.93347E+02  2.43495E+04 -2.97941E-02
   4.64000E+02 -6.84899E-07  1.35094E+02  2.43495E+04  1.66770E-02
   4.80000E+02 -1.80272E-06  8.09129E+01  2.43495E+04  4.38955E-02
   4.96000E+02 -2.44699E-06  3.78518E+01  2.43495E+04  5.95830E-02
   5.12000E+02 -2.86971E-06  9.98902E+00  2.43495E+04  6.98762E-02
   5.28000E+02 -3.23397E-06  6.14792E+02  2.43495E+04  7.87457E-02
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EXAMPLE 2  HOUSTON SHIP CHANNEL BRIDGE,HARRIS CO.,HIGHWAY I-610

 PILE NUM      DISTA,IN       DISTB,IN        THETA,RAD
    6        1.50000E+02    0.               1.66000E-01

     PX,LB        XT,IN           PT,LB        MT,IN-LB        YT,IN
 2.81481E+05   2.16524E-01   -1.16970E-01  -1.51905E+04-2.60572E-03
 INPUT INFORMATION

    TC     TOP DIA,IN    INC. LENGTH,IN NO. OF INC    KS    KA

    FIX      1.8000E+01     1.6000E+01       33          1     1

 PILE LENGTH,IN DEPTH TO SOIL  ITERATION TOL.BOUNDRY COND.2

    5.2800E+02     0.                1.0000E-03    -4.1831E-04

                             OUTPUT INFORMATION

      X,IN            Y,IN     MOMENT,IN-LB     ES,LB/IN          P LB/IN

  0.            2.62281E-02  1.53030E+05  1.81899E-12 -4.77086E-14
  1.60000E+01   1.99830E-02  1.54786E+05  5.33333E+02 -1.06576E+01
  3.20000E+01   1.46437E-02  1.53559E+05  1.06667E+03 -1.56200E+01
  4.80000E+01   1.02032E-02  1.48080E+05  1.60000E+03 -1.63252E+01
  6.40000E+01   6.62944E-03  1.38178E+05  2.13333E+03 -1.41428E+01
  8.00000E+01   3.86436E-03  1.24427E+05  2.66667E+03 -1.03050E+01
  9.60000E+01   1.82752E-03  1.07834E+05  3.20000E+03 -5.84805E+00
  1.12000E+02   4.21801E-04  8.95654E+04  3.73333E+03 -1.57472E+00
  1.28000E+02  -4.59709E-04  7.07465E+04  4.26667E+03  1.96143E+00
  1.44000E+02  -9.27156E-04  5.23132E+04  4.80000E+03  4.45035E+00
  1.60000E+02  -1.08843E-03  3.49330E+04  8.52372E+03  9.27744E+00
  1.76000E+02  -1.04524E-03  1.98702E+04  1.22474E+04  1.28015E+01
  1.92000E+02  -8.85762E-04  8.05194E+03  1.59712E+04  1.41467E+01
  2.08000E+02  -6.79156E-04 -1.58066E+02  1.96949E+04  1.33759E+01
  2.24000E+02  -4.73475E-04 -4.94359E+03  2.34186E+04  1.10881E+01
  2.40000E+02  -2.96727E-04 -6.88240E+03  2.43495E+04  7.22517E+00
  2.56000E+02  -1.60261E-04 -6.96024E+03  2.43495E+04  3.90228E+00
  2.72000E+02  -6.45311E-05 -6.02762E+03  2.43495E+04  1.57130E+00
  2.88000E+02  -4.07962E-06 -4.68282E+03  2.43495E+04  9.93369E-02
  3.04000E+02   2.89644E-05 -3.30488E+03  2.43495E+04 -7.05269E-01
  3.20000E+02   4.26657E-05 -2.10204E+03  2.43495E+04 -1.03889E+00
  3.36000E+02   4.40642E-05 -1.16170E+03  2.43495E+04 -1.07294E+00
  3.52000E+02   3.86636E-05 -4.94110E+02  2.43495E+04 -9.41441E-01
  3.68000E+02   3.03711E-05 -6.67180E+01  2.43495E+04 -7.39522E-01
  3.84000E+02   2.16881E-05  1.71466E+02  2.43495E+04 -5.28095E-01
  4.00000E+02   1.40087E-05  2.74175E+02  2.43495E+04 -3.41104E-01
  4.16000E+02   7.93390E-06  2.89110E+02  2.43495E+04 -1.93187E-01
  4.32000E+02   3.55123E-06  2.54112E+02  2.43495E+04 -8.64708E-02
  4.48000E+02   6.55815E-07  1.96559E+02  2.43495E+04 -1.59688E-02
  4.64000E+02  -1.08918E-06  1.34595E+02  2.43495E+04  2.65210E-02
  4.80000E+02  -2.04642E-06  7.91981E+01  2.43495E+04  4.98295E-02
  4.96000E+02  -2.54014E-06  3.64272E+01  2.43495E+04  6.18512E-02
  5.12000E+02  -2.82065E-06  9.43010E+00  2.43495E+04  6.86816E-02
  5.28000E+02  -3.04598E-06  5.58932E+02  2.43495E+04  7.41682E-02
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REFERENCES

1. Aschenbrenner, Rudolf, "Three-Dimensional Analysis of Pile Foundations," Journal of the Structural Division, American Society of Civil Engineers, Vol 93, February 1967, p 201.

2. Chellis, R. D., Pile Foundations, McGraw-Hill Book Co., New York, 1961, pp 19-35.

3. Chellis, R. D., "The Relationship Between Pile Formulas and Test Loads," Transactions, American Society of Civil Engineers, Vol 114, Paper No. 2369, 1949, p 290.

4. Coyle, Harry Michael, "Load Transfer for Steel Friction Piles in Clay," Dissertation submitted to The University of Texas, May 1965.

5. Fife, W. M., and Wilbur, J. B., Theory of Statically Indeterminate Structures, McGraw-Hill Book Co., New York, 1937, p 39.

6. Gleser, Sol M., "Lateral Load Tests on Vertical Fixed-Head and Free-Head Piles," Special Technical Publication 154, American Society for Testing Materials, 1954, p 75.

7. Hrennikoff, A., "Analysis of Pile Foundations with Batter Piles," Transactions, American Society of Civil Engineers, Vol 115, Paper No. 2401, 1950, p 351.

8. Matlock, Hudson and Reese, Lymon C., "Foundation Analysis of Offshore Pile-Supported Structures," Proceedings, Fifth International Conference, International Society of Soil Mechanics and Foundation Engineering, Paris, July 1961, Vol 2, p 91.

9. Matlock, Hudson and Reese, Lymon C., "Generalized Solutions for Laterally Loaded Piles," Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, Vol 86, October 1960, p 63.

10. McClelland, Bramlette and Focht, John A., Jr., "Soil Modulus for Laterally Loaded Piles," Transactions, American Society of Civil Engineers, Vol 123, Paper No. 2954, 1958, p 1049.

11. Meyerhoff, G. G., "The Ultimate Bearing Capacity of Foundations," Geotechnique, Vol 2, December 1951, p 301.

12. Meyerhoff, G. G., "Compaction of Sands and Bearing Capacity of Piles," Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 85, December 1959, p 1.

13. Olson, Roy E. and Flaate, Kaare S., "Pile-Driving Formulas for Friction Piles in Sand," Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, Vol 93, November 1967, p 279.

14. Reese, Lymon C. and Matlock, Hudson, "Behavior of a Two-Dimensional Pile Group under Inclined and Eccentric Loading," Proceedings, Offshore Exploration Conference, Long Beach, California, February 1966, p 123.

15. Reese, Lymon C., "Analysis of a Bridge Foundation Supported by Batter Piles," Proceedings, Fourth Annual Engineering Geology and Soils Engineering Symposium, Moscow, Idaho, April 1966, p 61.

16. Reese, L. C., "Load Versus Settlement for an Axially Loaded Pile," Symposium on Bearing Capacity of Piles, Central Building Research Institute, Roorkee, India, 1964, p 18.

17. Reese, Lymon C. and Matlock, Hudson, "Numerican Analysis of Laterally Loaded Piles," Proceedings, Second Structural Division Conference on Electronic Computation, American Society of Civil Engineers, Pittsburgh, 1960, p 657.

18. Reese, Lymon C., Discussion of paper by Bramlette McClelland and John Focht, Jr., Transactions, American Society of Civil Engineers, Vol 123, 1958, p 1071.

19. Robertson, Robert N., "The Analysis of a Bridge with Batter Piles," Thesis submitted to The University of Texas, January 1961.

20. Skempton, A. W., "The Bearing Capacity of Clays," Proceedings, Building Research Congress, Vol I, 1951, p 180.

21. Smith, Robert Earl, "A Method for the Analysis of Three-Dimensional Batter-Pile Foundations," Thesis submitted to The University of Texas, June 1961.

22. Terzaghi, Karl, "Evaluation of Coefficients of Subgrade Reaction," Geotechnique, Vol 5, December 1955, p 297.

23. Terzaghi, Karl, Theoretical Soil Mechanics, John Wiley and Sons, New York, 1943, pp 364-366.

24. Terzaghi, Karl, and Peck, Ralph B., Soil Mechanics in Engineering Practice, John Wiley and Sons, New York, 1967, pp 537-539.

25. Vetter, C. P., "Design of Pile Foundations," Transactions, American Society of Civil Engineers, Vol 104, Paper No. 2031, 1939, p 758.